Six Sigma Model to Improve the Lean Supply Chain in Ports by System Dynamics Approach

Von der Fakultät für Ingenieurwissenschaften,
Abteilung Maschinenbau und Verfahrenstechnik der

Universität Duisburg-Essen

zur Erlangung des akademischen Grades

eines

Doktors der Ingenieurwissenschaften

Dr.-Ing.

genehmigte Dissertation

von

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Tag der mündlichen Prüfung: 24.10.2016

Abstract

Ports are one of the important sectors of the national economy of a country and are primarily involved in the import and export of goods and services from one point to another, such as between the sea, river, road, and railways. The quality of a port is one of the important aspects to make a port attractive. The lean supply chain in ports is one of these attractive aspects. This research aims to design a six sigma model to improve the lean supply chain in ports. Six sigma model can be built by using system dynamics approach which enables to take into account dynamics variables. The lean supply chain in ports focuses on eliminating sources of "waste" in the entire flow of material in the cargo-handling process. The types of waste in ports have been identified as the delay time of equipment and transporters, lost and damaged cargo, equipment and transporter breakdowns.

This research begins with the research formulation and definition of objectives. After that, the model conceptualization is constructed using a causal loop diagram based on the objective, a literature study, and field study. The causal relationships between variables are determined by historical data in real cases, from the literature, and from expert judgements. The model is validated with a real case in CDG Port in Indonesia and simulated using Powersim software. By simulating the process from the base case model, it is possible to propose a policy for improvement scenarios. Regarding the simulation results in the base case, it has been found that the high berth occupancy ratio (BOR), which influences the congestion that is indicated by the vessel waiting time, is one of the key performance indicators in port operation. Also, the demurrage and repair costs contribute most to the total cost of poor quality, followed by the cost of lost cargo. The demurrage cost is caused by the delay time of equipment and transporters, and the repair cost is caused by equipment and transporter breakdown.

Regarding the results of improvement scenarios, it can be concluded that increasing the operation cycle of the crane along with its lifting capacity can reduce the vessel waiting time as a key performance indicator in the port. Also, the increase of transport maintenance items, number of inspectors, and safety and security costs can reduce the costs arising from demurrage, repair, and lost cargo. The port performance is measured by the sigma value and the process capability indices as the performance metrics. These metrics are utilized to eliminate waste in order to improve the lean supply chain in the port. With this model, and changing the sigma value and the process capability indices of the waste, the results can be identified and analyzed.

Zusammenfassung

Häfen sind einer der wichtigsten Sektoren der Volkswirtschaft eines Landes und sind im Wesentlichen auf den Im- und Export von Waren und Dienstleistungen von einem Punkt zum anderen beteiligt, wie z.B. zwischen Meer, Fluss, Straße und Schienen. Die Qualität eines Hafens ist einer der wichtigsten Aspekte, um einen Hafen attraktiver zu machen. Die Lean Supply Chain in Häfen ist einer dieser attraktiven Aspekte. Diese Arbeit zielt darauf ab, ein Six-Sigma-Modell zu entwerfen, um die Lean Supply Chain in Häfen zu verbessern. Das Six-Sigma-Modell kann mit Hilfe von der Systemdynamik-Methode abgebildet werden, damit diese die Betrachtung der dynamischen Variablen ermöglicht. Die Lean Supply Chain in Häfen konzentriert sich auf die Beseitigung von Verlustursachen im gesamten Materialfluss während des Umschlagprozesses. Als Verlustarten in Häfen wurden die zeitliche Verzögerung durch Gerätschaften und Transporter, verloren gegangene und beschädigte Ladung, sowie Defekte an den Gerätschaften und Transportern identifiziert.

Diese Arbeit beginnt mit der Beschreibung der (aktuellen) Forschung und Festlegung der Ziele. Danach wird das Modell mit einem Ursache- und Folgediagramm, auf der Grundlage der Ziele, sowie einer Literatur- und Feldstudie, konstruiert. Die kausalen Beziehungen zwischen den Variablen werden mittels historischer Daten zu realen Fällen, aus der Literatur und aus Expertenurteilen bestimmt. Das Modell wird mit der Software Powersim simuliert und mit dem realen Fall des CDG-Hafens in Indonesien validiert. Es ist möglich, auf der Grundlage von Simulationen des Base-Case-Modells eine Strategie für die Verbesserungsszenarien vorzuschlagen. Bezüglich der Ergebnisse der Simulation im Basisfall, hat es sich gezeigt, dass einer der wichtigsten Performance-Indikatoren im Hafenbetrieb das hohe Anlegeplatz-Besetzungsverhältnis (BOR) ist, welches die Überlastung beeinflusst, was sich an den Schiff-Wartezeiten erkennen lässt. Zusätzlich tragen Liegegebühr und Reparaturkosten am meisten zu den Gesamtkosten von schlechter Qualität bei, gefolgt von den Kosten für verlorene Ladung. Die Liegegebühr wird durch die Verzögerung durch Ausrüstung und Transporter verursacht und die Reparaturkosten durch den Defekt von Ausrüstung und Transportern.

Hinsichtlich der Ergebnisse der Verbesserungsszenarien kann geschlussfolgert werden, dass die Wartezeit als ein Schlüsselindikator für die Leistungsfähigkeit eines Hafens durch die Erhöhung des Arbeitszyklus und der Hebeleistung der Kräne reduziert werden kann. Außerdem kann auch durch Erhöhung der Wartungsanzahl und der Ausgaben für Sicherheit die Kosten für Liegegebühren, Reparaturen und verloren gegangene Ladungen reduziert werden. Die Leistung des Hafens wird durch die Leistungskennwerte des Sigma-Wertes und der Prozessfähigkeitsindizes gemessen. Diese Kennzahlen werden für die Beseitigung von Verlusten verwendet, um die Lean Supply Chain im Hafen zu verbessern. Mit diesem Modell und der Änderung des Sigma-Wertes und der Prozessfähigkeitsindizes der Verluste, können die Ergebnisse identifiziert und analysiert werden.

Acknowledgement

All Praises to The Almighty God, Allah SWT, for His graces, His guidance, and His help throughout my life.

Firstly, I would like to express my sincere gratitude to my main supervisor, Prof. Dr.-Ing. Bernd Noche, for the scientific discussions and guidance in my Ph.D. study. Also, I would like to thank Prof. Dr.-Ing. Bettar Ould el Moctar and Prof. Dr.rer.pol. Rainer Leisten as the second and the third supervisor for their inputs and recommendations.

Special thanks to all academics and technical staffs of Transport System and Logistics Institute for their many helpful discussions and administrative support.

My sincere appreciation to my greatest parents, H.E. Soemarna and Hj. Popong, and my beloved wife, Hj. Suci Widaryati, which they always pray for me anytime to finish my Ph.D. Also, my children, Arid, Najmah, Hadiyan, and Ghaida, who give me the support and motivation.

At last but not least, I would like to thank for my scholarship sponsors, Ministry of Research, Technology and Higher Education- Republic of Indonesia, my colleagues in Indonesia, Rector of Sultan Ageng Tirtayasa University and Operation General Manager of CDG Port, and all my friends in Germany. All of them always support me to finish my Ph.D. study.

" …*And whosoever fears Allah, He will create for him a way out. And will provide for him where he didn't expect…*"

Quran, 65:2-3

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List of Abbreviations

ANOVA	Analysis of Variance
BOR	Berth Occupancy Ratio
COPQ	Cost of Poor Quality
CLD	Causal Loop Diagram
DMAIC	Define Measure Analyze Improve Control
DMADV	Define Measure Analyze Design Verify
DWT	Dead Weight Tonnage
DPMO	Defects per Million Opportunities
DLLC	Double Level Luffing Crane
FMEA	Failure Mode Effect Analysis
JIT	Just In Time
KPI	Key Performance Indicators
LSL	Lower Specification Limit
LWS	Low Water Spring Tide
MPC	Multipurpose Crane
PAF	Prevention Appraisal Failure
PDCA	Plan Do Check Action
PCI	Process Capability Indices
PQL	Port Quality Level
PO	Port Operation
PPM	Port Performance Metrics
PHC	Portal Harbour Crane
QFD	Quality Function Deployment
RSM	Response Surface Method
SFD	Stock Flow Diagram
SPC	Statistical Process Control
SD	System Dynamics
SCM	Supply Chain Management
SIPOC	Supplier Input Process Output Customer
SV	Sigma Value
TQM	Total Quality Management
TPS	Total Production System
TPM	Total Productive Maintenance
USL	Upper Specification Limit
VSM	Value Stream Mapping

List of Notations

AC	*the appraisal cost*
Bn	*the number of berths*
Cc	*the operation cycle of crane*
Ct	*the operation cycle of truck*
Cpk	*the process capability indices (actual)*
CpU	*the process capability indices (upper)*
CpL	*the process capability indices (lower)*
CTQ	*critical to quality*
CC	*the conformance cost*
CCR	*the conformance cost rate*
CDC	*the cargo damage cost*
CLC	*the cost per lost cargo*
CI	*the cost per inspector*
CAC	*the complaint adjustment cost*
ct	*the capacity of tugboat*
DC	*the demurrage cost*
DM	*the delay due to maintenance*
DR	*the delay due to repair*
DCH	*the demurrage cost per hour*
DCC	*the discount due to damaged cost*
df	*the delay factor*
df	*the degree of freedom (ANOVA)*
dt	*the time interval between periods*
EFC	*the external failure cost*
EFCR	*the external failure cost rate*
ERT	*the equipment repair time*
EMT	*the equipment maintenance time*
Lcc	*the lifting capacity of crane*
Lt	*the capacity of truck*
LCC	*the lost cargo cost*
MS	*means square*
MTT	*the maintenance time per transporter item*
Nb	*the actual number of tugboats*
Nbd	*the desired number of tugboat*
Nc	*the actual number of cranes*
Ncd	*the desired number of crane*

Nt	*the actual number of trucks*
Ntd	*the desired number of truck*
NCC	*the non-conformance cost*
NCCR	*the non-conformance cost rate*
NTM	*the number of transporter maintenance items*
NI	*the number of inspectors*
Orsy	*the delivery rate of cargo in the stockpile yard*
Orwh	*the delivery rate of cargo in the warehouse*
Oct	*the operation cycles of tugboat*
Pb	*the productivity of tugboats*
Pc	*the productivity of cranes*
Pcy	*the productivity of conveyors*
Pt	*the productivity of trucks*
PC	*the prevention cost*
PCR	*the prevention cost rate*
RC	*the repair cost*
RTT	*the repair time per transporter item*
SS	*sum of square*
Ssy	*the stock in stockpile yard*
Sv	*the actual number of unloaded vessel*
Svd	*the desired number of unloaded vessels*
Swh	*the stock in warehouse*
SSC	*the safety and security cost*
t	*time step*
tav	*the adjustment time for arrival rate of vessel*
Tb	*the approach time of a vessel*
Tber	*the berthing time of a vessel*
tat	*the adjustment time for the rate of trucks*
tac	*the adjustment time for the rate of cranes*
tab	*the adjustment time for the rate of tugboats*
ta_{cy}	*the adjustment time for the rate of conveyor speed*
ta_{co}	*the adjustment time for the cost of poor quality rate*
ta_{cc}	*the adjustment time for the conformance cost rate*
ta_{pc}	*the adjustment time for the prevention cost rate*
ta_{nc}	*the adjustment time for the non-conformance cost rate*
ta_{ic}	*the adjustment time for the internal failure cost rate*
ta_{ec}	*the adjustment time for the external failure cost rate*

ta_{oc}	*the adjustment time for the opportunity cost rate*
ta_{tb}	*the adjustment time for the rate of the number of transporter breakdown*
ta_{tmc}	*the adjustment time for the rate of the transporter maintenance cost*
ta_{dc}	*the adjustment time for the demurrage cost rate*
ta_{dr}	*the adjustment time for the delay due to repair*
ta_{dm}	*the adjustment time for the delay due to maintenance*
ta_{lcc}	*the adjustment time for the lost cargo cost rate*
ta_{lc}	*the adjustment time for the amount of lost cargo rate*
TRsy	*throughput in stockpile yard*
TRwh	*throughput in warehouse*
Ts	*the vessel service time*
TRT	*the transporter repair time*
TBT	*the number of transporter breakdown items*
TMT	*the transporter maintenance time*
TMC	*the transporter maintenance cost*
Tw	*the vessel waiting time*
ERT	*the equipment repair time*
Wd	*the number of days per month*
Wh	*the number of hours per day*
Wv	*the load per vessel*
$\bar{u}$	*the sample average for discrete data*
$\bar{X}$	*the sample average*
σ	*a natural tolerance*

Chapter 1

Introduction

1.1 Research Problems

Many activities in the supply chain at ports are inefficient and ineffective. Therefore, several methods and tools are applied to improve the performance of the logistics and supply chain at ports. These activities need to be well organized, planned and controlled. The logistics and the supply chain have an important strategic function in enabling companies to achieve competitive advantage. The flow of goods and services at the port is a complex system. Ports are an important sector of the national economy of a country, and are primarily involved in the import and export of goods and services from one point to another, such as between the sea, river, road, and railways. The value added to goods and services in the port depends on the effective and efficient supply chain flow through the cargo-handling process.

Many types of waste can occur in the cargo-handling process, including equipment or transporter delays, overload of inventory, cargo loss or damage, etc. This research uses the lean supply chain approach to identify and map the waste in the supply chain through the cargo-handling process at the port. The lean supply chain has been developed by integrating supply chain management and lean manufacturing. Phelps et al. (2003) stated that lean manufacturing is the common name for concepts exemplified by the Toyota Production System, in the process of eliminating sources of waste in the manufacturing process. The lean approach can be implemented not only in manufacturing but also in the service industry, including at a port. The purpose of the lean approach is to create value for the customer. Womack and Jones (2003) stated that the first step in lean thinking is to specify that value accurately.

Lean, in the supply chain through the cargo-handling process at a port, means trying to eliminate waste to give value for the customer. Phelps et al. (2003) stated that the lean supply chain was built on providing value to the customer by optimizing the performance of the supply chain system. Also, lean in the supply chain can reduce costs by eliminating waste, so increasing the profit. Agarwal et al.(2006) stated that leanness in a supply chain maximizes the profits through cost reduction. Khataie and Bulgak (2013) introduced a cost of quality decision support model to reduce the waste factors. Some researchers have implemented a lean supply chain to achieve higher performance. Wee and Wu (2009) implemented a lean supply chain at Ford Motor Company by value stream mapping (VSM). Agus and Hajinoor (2012) stated that the lean production supply chain contributed to enhancing the product quality program and business performance. Cudney and Elrod (2011) presented the effectiveness of lean techniques in the supply chain using a survey administered in multiple industries.

This research uses the Six Sigma methodology approach to improve the lean supply chain regarding the excess process variability in cargo handling at ports. Originally, the six sigma process comes from the PDCA cycle (plan, do, check, action) or the Deming cycle. Motorola (1980) developed the six sigma DMAIC process (define, measure, analyze, improve, control). Based on Yang et al. (2007), another methodology, the DMADV process (define, measure, analyze, design, verify), was used by General Electric (GE) Medical Systems in the process management and process redesign in six sigma. The six sigma DMAIC process is adopted at the design or re-design stage of the product or process (Tjahjono et al., 2010).

Some researchers have implemented the six sigma methodology in ports. They designed a six sigma methodology to measure and reduce problems at the port such as equipment breakdown, damaged or lost cargo, etc. Nooramin et al. (2011) examined the six sigma methodology in marine container terminals to reduce the truck congestion. Jafari (2013a) investigated the efficiency rate of container loading and unloading process. Garg et al.(2004) presented the reduction of variability, synchronization, and improvement in delivery in the supply chain networks.

Regarding the complex systems in ports, this research uses system dynamics to improve the lean supply chain. System dynamics is an appropriate tool to determine the causalities between variables and the behavior of the system as a whole, especially in a complex system with its dynamic characteristics. Some researchers have designed models using the system dynamics approach. Briano et al. (2009) built a model of the VTE (Voltri Terminal Europe) container terminal to achieve an efficient decision cockpit that connected with the ERP (Enterprise Resource Planning) system. Mei and Xin (2010) developed a model of the port operation system with a focus on time, quality, and profit.

The integration of six sigma models and system dynamics in ports has not yet considered by previous studies. This study seeks to fill the research gap by integrating a six sigma model and system dynamics to improve the lean supply chain in ports.

1.2 Problem Statement

Many activities in ports are sources of waste such as delay time and breakdown of equipment and transporter, lost and damaged cargo, and vessel waiting time, so a breakthrough is required to achieve improved performance. The lean supply chain contributes to eliminating waste in the entire supply chain. Many researchers have developed lean supply chains in manufacturing companies (Wee and Wu, 2009; Arawati and Hajinoor, 2012; Khataie and Bulgak, 2013) and service industries like the government, military, and finance (Cudney and Elrod, 2011). This research developed a lean supply chain to eliminate waste in the whole of the supply chain in ports. At the same time, the six sigma methodology is known as a breakthrough in total quality management (TQM) to reduce process variability. Some researchers have investigated six sigma methodology in ports (Nooramin et al., 2011; Jafari et al., 2013). This research developed a six sigma model to reduce the process variability of cargo handling process, caused by delay time, equipment breakdowns, rejects, rework, etc.

The complexity of port requires a tool that can model its system. One of these tools is system dynamics which is well-known for understanding the dynamic behavior of the complex system. Six sigma model can be built by using system dynamics approach which enables to take into account dynamics variables. Some researchers are using System Dynamics in ports (Briano et al., 2009; Mei and Xin, 2010).This research proposes to build a model that integrates a six sigma model with system dynamics to improve the lean supply chain in a port. Six sigma is focused on measures of the cost of poor quality, the sigma value, and the process capability indices, which is caused by the equipment and transporter delay times, lost or damaged cargo, or equipment and transporter breakdown. Lean in the supply chain focuses on eliminating waste, which increases costs because of poor quality, in the supply chain at the port.

1.3 Research Objectives

This research focuses on designing a six sigma model to improve the lean supply chain in ports using the system dynamics approach. The detailed research objectives are explained below:

1. Designing a general six sigma model related to the lean supply chain at ports.
    a. Integrating a model of the port operation, the port quality level, and the port performance metrics with the causal loop diagram.
    b. Developing causal relationships between variables in ports dynamically with the mathematical formulation.
    c. Measuring the port performance baseline with the sigma value and process capability indices as performance metrics for the waste in ports.
    d. Determining the behavior of the simulation results of the base case simulation and finding their causes.
2. Improving the lean supply chain with model simulations using the system dynamics approach.

a. Decreasing the vessel waiting time in ports that causes congestion by checking the berth occupancy ratio (BOR) value so that the port's performance will increase.
b. Decreasing or eliminating waste as the internal failure cost, such as the costs of demurrage, repair, lost cargo, and damaged cargo in ports.
c. Decreasing the cost of poor quality (COPQ), to improve the lean supply chain in ports.
d. Improving the sigma value and process capability indices of the waste as the internal failure activities in ports.

1.4 Significance and Contribution of Research

There are several significant aspects for both researchers and practitioners as follows:

1. Studies on integration between the six sigma model and system dynamics in ports which has not yet considered by previous studies, according to the literature review. Many researchers have studied six sigma and system dynamics only partially. Also, the area of study for many researchers has been more in the manufacturing industries, especially as concerns six sigma methodology.
2. A port is a complex system and the interaction between variables are dynamic, and this model can assess the behavior of a system with a causal loop diagram. The behavior of the complex system in ports can be defined clearly. The causal loop diagram can establish the causal relationship between variables and the feedback loop for all the causal relationships. Also, the behavior of the system in ports can be analyzed and causes can be determined.
3. This contributes to making policy improvements in some scenarios in ports with system dynamics simulations. These simulations can create improvement scenarios enabling decision makers to take action in the future. Policies for improvement can be developed for several time durations dynamically. These scenarios can be selected according to the objectives of the decision makers.
4. The port's performance can be measured directly using the sigma value, process capability indices, and cost of poor quality in the simulation. The sigma value will determine whether the quality of the port performance is good or not. The degree of defects or non-conformance can be measured. Meanwhile, the process capability indices will establish whether the process capability of the port is capable or not of meeting the customer requirements or specifications. The cost of poor quality will determine the cost impact of the poor quality. These metrics measure the sources of waste in the cargo-handling process at ports such as lost and damaged cargo,

equipment and transporter breakdown, and the delay time of equipment and transporters.

There are several significant contributions of this research as follows:

1. The six sigma model will give the decision makers to make some scenarios to contribute for the optimization of performance in ports. Decision makers can create and select improvement scenarios based on their objectives. The improvement scenarios will contribute to find the best performance in ports.
2. The six sigma model can assess the causal relationships in ports as a complex system. A port is a complex system and the interaction between variables are dynamics. This model can determine the causal relationships between variables with mathematical formulations determined both by the literatures and the expert judgements. Afterward, this model can assess the behavior of these causal relationships and find their causes.
3. The six sigma model will improve the performance in ports directly with the sigma value, the process capability indices, and the cost of poor quality as performance metrics. The improved performance in ports is quantified by the performance metrics of six sigma methodology. Improving the values of the sigma value, the process capability indices, and the cost of poor quality in the simulation, indicate the port's performance improve to reach the target of the metrics.

1.5 Organization of the Thesis

The organization of this thesis is based on the steps conducted in this research. Each chapter is based on the structure of thesis, as follows:

Chapter 1: Introduction

This section contains the problems in the port viewed as a complex system and some of the finished research. The research focus is stated in the problem statement. The purpose of the research is formulated based on the problem statement. The research significance is conveyed to indicate the contribution of the research.

Chapter 2: Literature Review

This section contains the literature survey about the lean supply chain concept, six sigma methodology concept, simulation of system dynamics, and port as an industry. This literature supports the understanding of the concepts applied in this research.

Chapter 3: Research Methodology

This section contains the methods and tools used in the research. Also, this section provides a general research framework. Therefore, it is well defined from the beginning to the end systematically.

Chapter 4 Model of the Causal Loop Diagram

This chapter contains the design of the causal loop diagram of the six sigma model in the port. This causal loop diagram assesses the conceptual model of the six sigma model applied.

Chapter 5 System Dynamics with the Stock Flow Diagram

This chapter contains a design of the stock flow diagram of the six sigma model in the port. This diagram utilizes a system dynamics concept dependent on time. The mathematical formulation defines the relation between variables.

Chapter 6 Empirical Analysis

This chapter contains the case study to prove the model in the real case. The validation process is conducted to prove the model using real data in the port. CDG Port, Indonesia was selected to carry out this validation. The baseline performance is determined based on the six sigma concept by measuring the sigma value, the process capability indices, and the cost of poor quality.

Chapter 7 Improvement Policy Scenarios and Analysis

This chapter contains the design of the policy for improvement by making changes or adding input parameters or a feedback loop. Then, the behavior of the model is analyzed and causes are found. Evaluation of the model is performed using the performance metrics of the sigma value, the process capability indices, and the cost of poor quality.

Chapter 8 Conclusions and Future Research

This chapter contains conclusions and recommendations for future research.

Its structure can be seen in Figure 1 below:

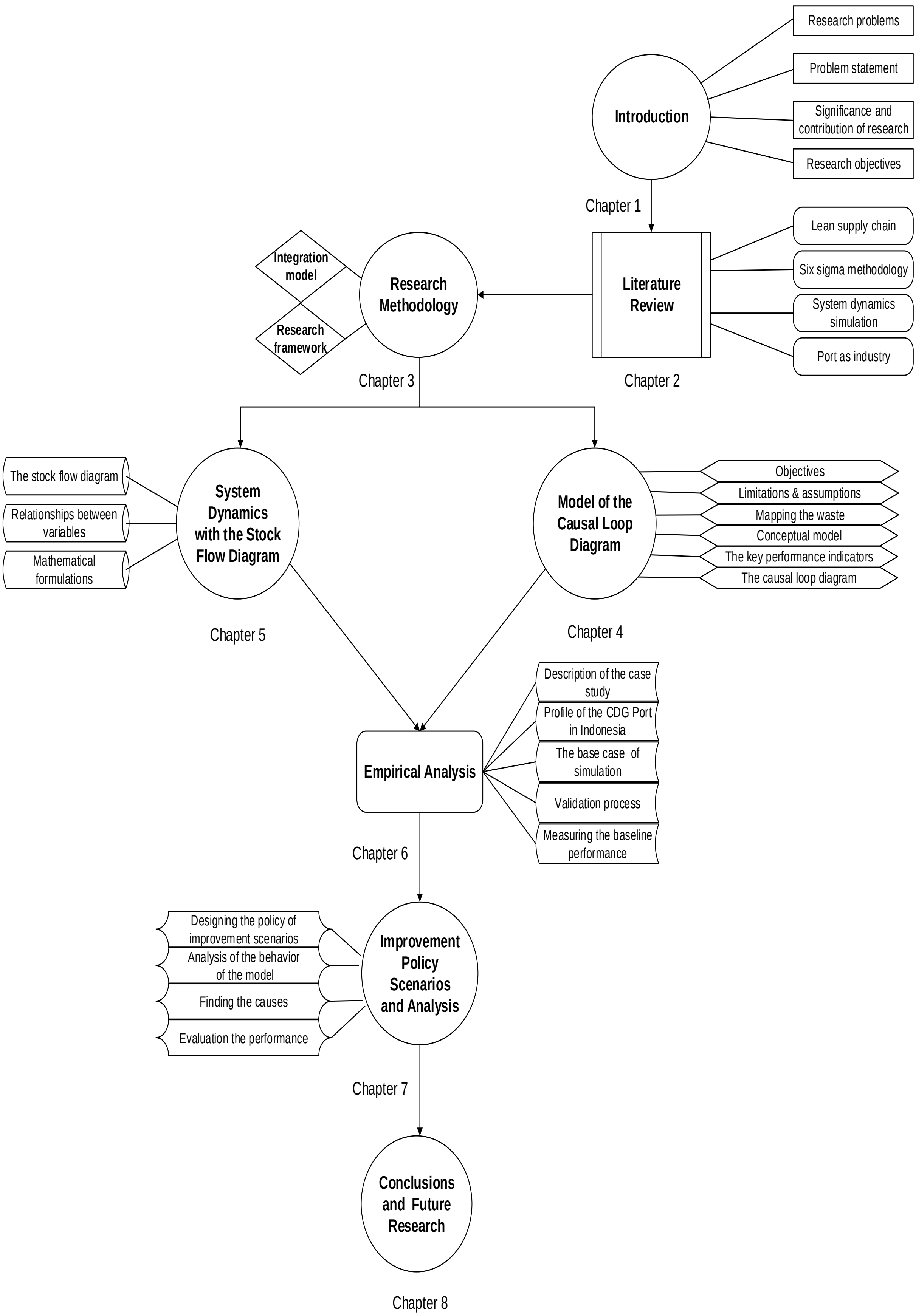

Figure 1.Structure of thesis

Chapter 2

Literature Review

In this chapter, three parts are elaborated as follows: 1) overview of lean supply chain concept; 2) overview of six sigma methodology; 3) overview of simulation with system dynamics; 4) overview of the port as industry.

2.1 Overview of Lean Supply Chain

Lean Supply Chain (LSC) is a concept to manage the supply chain becomes lean or free from the waste or non-value added activities. Lean concept has applied to the supply chain to eliminate or reduce the waste as inefficiencies in collaborating and partnering with the suppliers and customers.

2.1.1 Lean concept

The term 'lean' or 'lean thinking' originally comes from a lean concept used in the Toyota Production System (TPS) in 1990. TPS established the fundamentals of the lean thinking, as popularized by Womack and Jones (1996). This approach was developed in the manufacturing industry after the second world war, initiated by Taiichi Ohno and associates while working with Toyota motor company (Pepper and Spedding, 2009). Womack and Jones (2003) mention two of the fundamental lean principles in physical production at Toyota: 1) Automatic machines on a line that will stop when a mistake occurs, known as jidoka; 2) A pull system so that only the parts needed are made. Also, Womack et al.(1990) identify the gap between Toyota's quality and productivity and that of automobile manufacturers in the United States and Europe. They also discuss lean production to describe the innovative production system that separates craft production and mass production. Lean concept is reflected as a pull system that produces goods or services based on the demand to reduce the inventory. Näslund (2008) mentions that there are five basics for the lean process steps: 1) specifying value and all value added aspects in the process; 2) recognizing the value stream; 3) pushing the activities to flow without disruption; 4) permitting the customer to pull the product or service over the process; 5) continuously overtaking perfection of the process.

Andersson et al.(2006) explain the benefits of lean, such as decreasing the work in process and cycle time, increasing the inventory turns and capacity utilization, and improving customer satisfaction. These improvement areas include operational improvements (the reduction of lead time and work in process, increasing productivity, etc.); administrative improvements (the reduction of processing errors, etc.); and strategic improvements (reduced costs, etc.). The success of Toyota with the lean concept has spread to other companies. El-Haik and Roy (2005) declare that the majority of measures in a service or process will focus on speed, cost, quality, efficiency, and effectiveness. This concept aims to achieve high speed, low cost, high quality, high efficiency, and high effectiveness. According to Hines et al. (2004), the development of lean thinking consists of: 1) cells and assembly lines; 2) shop-floor; 3) value stream; and 4) value systems. Mason et al. (2014) mention that lean is an improvement method to focus on designing and adjusting process pathways to maintain the stages that serve a value and eliminate the sources of waste.

The lean concept focuses on eliminating sources of waste. According to Liker and Meier (2006), Toyota identifies seven major types of non-value added activities or seven types of waste in a business or manufacturing process, namely: overproduction, waiting (time on hand), transportation/conveyance, over-processing or incorrect processing, excess inventory, unnecessary movement, and defects. Ohno considers that overproduction is a fundamental waste since it causes most of the other waste. Therefore, tools are needed to map all the activities in the supply chain flow. A value stream map (VSM) is one of the tools in lean thinking in the field. With the lean concept, waste can be eliminated using the value stream mapping tools. There are basic lean tools such as standardized work, visual job aids, visual workplace, and 5S (sort out, shine, set in order, standardize, sustain), as well as advanced lean tools consisting of batch size reduction and quick changeover, kanban, quality at the source, work cell, and total productive maintenance (TPM) (Myerson, 2012). The basic and advanced lean tools are depicted in Figure 2 as a House of Lean as follows:

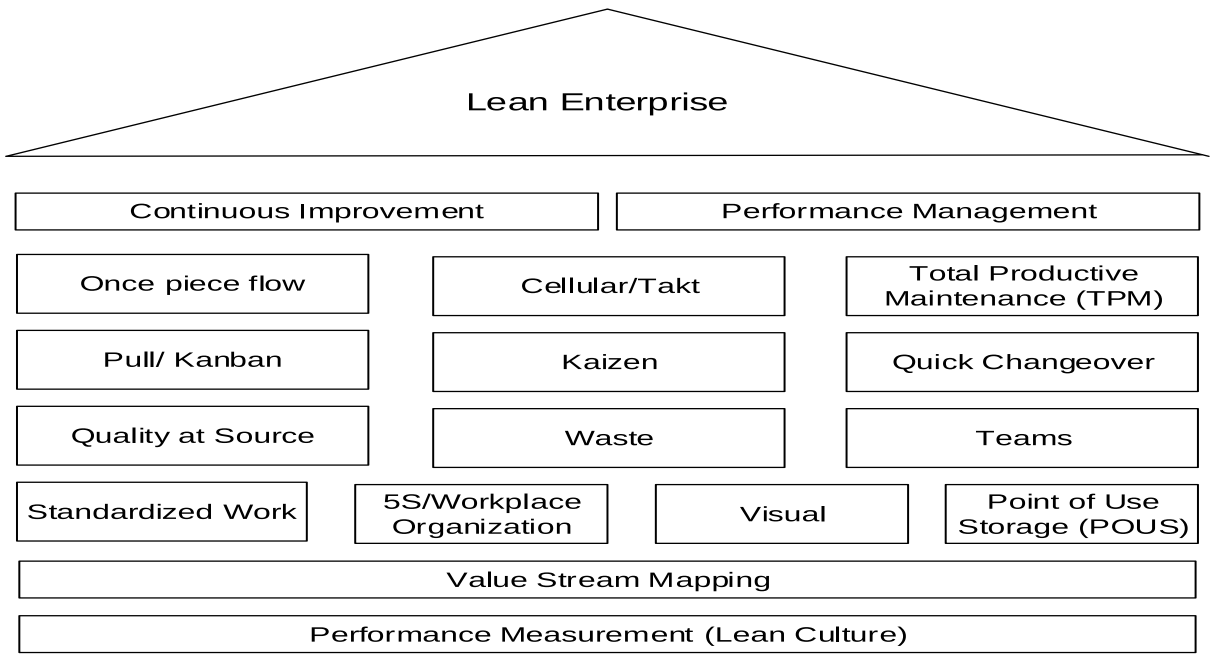

Figure 2.House of Lean (Myerson, 2012)

Also the lean concept focuses on creating a value for the customer. Creation of a value can reduce the cost. Hines et al. (2004) verify the relationships between the value of customer and the cost in detail. The cost-value equilibrium shows the position where the product presents much value which the customer is willing to pay the costs of product. The value will be created if there is migration from the reduction of waste to the value of customer, i.e.: 1) value is established if the internal waste is decreased; and 2) value is enhanced if the additional features or services are proposed. Lean has a target to reduce the non-value added activities so the processes become more efficient. Therefore, lean concept need to understand a process both how the process is working and the variation is appearing from it (Lighter, 2014).

2.1.2 Supply Chain Management (SCM)

Nowadays, the supply chain has become a critical strategic function to win over the competition in a global market. Many kinds of literature distinguish between logistics and the supply chain. The Council of Logistics Management (1998) in Lummus et al.(2001) defines logistics as part of the supply chain as: "*the process planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements"*. Sutherland in Ayers (2000) define a supply chain as: "*Life cycle processes comprising physical, information, financial, and knowledge flows whose purpose is to satisfy end-user requirements with products and services from multiple linked suppliers*". Beamon (1998) defines a supply chain is a set of links between suppliers, manufacturers, distributers, and retailers that simplifies the transformation of the raw materials into the end products. At the highest grades, the supply chain involves two basics to integrate the processes: 1) the production planning and inventory control, and 2) the distribution and logistics. The supply chain needs to be managed and arranged, so supply chain management (SCM) has developed.

Supply chain management was originally introduced by Oliver R.K. and Webber M.D., in the early 1980s. Ayers (2000) defines SCM as: *"design, maintenance, and operation of supply chain processes for the satisfaction of the end user needs".* Mentzer et.al. (2001) define SCM as: *"the systemic, strategic coordination of the traditional business functions and the tactics across these business functions within a particular company and across businesses within the supply chain, for the purposes of improving the long-term performance of the individual companies and the supply chain as a whole"*. SCM comprises multiple company activities in the supply chain. Nevertheless, the supply chain is not just business-to-business relationships, but it is a multiple business and relationships network. SCM deals with the excellence of the total business process and reflects a new method to manage business and relationships between components of the supply chain (Lambert et al., 1998). Li et al. (2006) state that the SCM practices have an effect to the competitive advantage and organizational performance of a company.

It is very challenging to manage the supply chain because of the complexity of all tiers from the origin point to the consumption point. Supply chain management involves applying a total systems approach to managing all of the material, information, and service flows, from suppliers of raw material through factories and warehouses to the end customer (Chase, 2004). The supply chain network from the suppliers of raw material to the end of costumer is one of the key factors that must be known and understood. Lambert et al. (1998) mention that there are three primary aspects of the structure of a company's network: 1) the supply chain components; 2) the network structural dimensions; 3) the different kinds of process relationships over the supply chain.

SCM has become the main issue in improving the performance of a manufacturing or service company. Each company tries to develop supply chain strategies. According to Chopra and Meindl (2007), the success or failure of a company is closely related to the following key factors: 1) the competitive strategy and all function strategies must fit together to establish a coordinated general strategy; 2) the different functions in a company must properly structure their processes and resources to perform these strategies successfully; 3) the design of the overall supply chain and the role in each level must be strengthened to contribute the supply chain strategy. Many strategies have been considered to improve the performance. The capabilities of supply chain organizational and information technology enable companies to improve the supply chain performance (Sweet and Lee, 2009).

Modeling the supply chain is performed to measure and analyze the supply chain performance. Beamon (1998) categorizes the modeling approach in this concept: 1) models of deterministic analytics; 2) models of stochastic analytics; 3) models of economic aspects; and 4) models of simulation. The performance metrics for modeling the supply chain are presented as a function of one or more input parameters. These input parameters as the decision variables are selected to improve the performance metrics. Akkermans and Dellaert (2005) state that there are three common approaches to improve the supply chain performance: 1) data-driven; 2) the improvement of process; and 3) the theory of control approach. Three domains of the methodology in supply chain study, i.e.: 1) the discrete time; 2) the continuous time; and 3) the control theory approach.

2.1.3 Lean Supply Chain

Nowadays, integration between the lean concept and the supply chain has become a new concept known as the Lean Supply Chain. Martin (2010) defines the lean supply chain as

…"*one in which all participants perform according to lean principles including level schedule loading using pull-based demand, deployment of continuous improvement activities, maintenance of sufficient (even excess) capacity to satisfy external demand, strict schedule adherence to optimize profit for all participants across the supply chain, and establishment of long-term reciprocal relationships among all participants*"... Lean in the supply chain means how to eliminate waste in the supply chain. This waste must be identified and mapped so that the improvements can be made. According to Myerson (2012), the most efficient way to identify waste is by value stream mapping (VSM), similar to a flowchart or process flow map, but one of the key differences is that the "current state" map identifies non-value-added and value-added activities. El-Haik and Roy (2005) mention that the process mapping can be utilized to develop a value stream map to understand how the process is performing well in terms of value and flow. VSM supports the lean supply chain and recognizes the potential opportunities for eliminating the waste (Wee and Wu, 2009). VSM utilizes the pull system and consists of the current state mapping and the future state mapping. The current state mapping indicates an actual condition of the process, including the material flow. The future state mapping is designed to improve the performance of the process. Liker and Meier (2006) mention that there are seven elements to be expected in the future state mapping, i.e.: 1) flexibility; 2) short lead time; 3) linked process; 4) flow loops; 5) streamlined information flow; 6) consciousness of the customer need; and 7) pacemaker.

Lean supply chain concept has been implemented in several industries because the entire supply chain system is very complex. Each company tries to apply the lean supply chain to become competitive. Martin (2007) mentions that the lean supply chain aims at reducing the complexity of the system and sending products and services at detailed cost, free of defect, and on time over numerous business entities and organizational in the supply chain to the end customer. There are many techniques and tools that can be used to implement the lean supply chain to reduce operational costs and task time variations, improve the quality of products and services, and serve the customer with customization and flexibility. Arnheiter and Maleyeff (2005) mention that decreasing supplier variability can be reached by the partnerships and the collaboration between supplier and producer. Some company policies try to reduce the bullwhip effect to contribute the optimization of performance. The practices of quality management in the lean production emphasize the zero quality control concept which involves source inspection, mistake proofing, automated 100 percent inspection, stopping operation when a mistake is created, and confirming setup quality (Shingo in Agus and Hajinoor (2012).

According to Martin (2007), there are three characteristics of the lean supply chain at an operational level: 1) rate-based demand and production smoothing; 2) a mixed-model production schedule; 3) demand pull scheduling system. Lean supply chain is denoted by the ability to respond and anticipate to the customer demand dynamically. The trade-off between the production cost, lead-time of supply, and unpredictability of demand within the sector continues to take action as a focus for improved responsiveness and developed relationships (Bruce and Daly, 2004). The lean supply chain assesses each stage in the entire supply chain from suppliers until customers. Lamming (1996) mentions that the entire material flow in the supply chain from raw materials to the end users is taken into account as an integrated system.

According to Phelps et al.(2003), the steps for building the lean supply chain are as follows: 1) select the target of the supply chain; 2) appraise the current state of the supply chain; 3) determine how best to move forwards; 4) implement the change in the supply chain; and 5) share the results with current and prospective customers as well as other suppliers in the same and other supply chains. These steps can be implemented with the coordination and collaboration between players in the supply chain. The main goal of building the lean supply chain is to reduce the waste in the entire supply chain and improve the customer order rate. Myerson (2012) states that an efficient lean supply chain can be used not only to improve the financial and operational aspect of a business but also as a competitive tool. Naylor (1999) proposes the combination of lean and agile paradigms to design and operate the total supply chain. The company needs the agility to satisfy a changeable demand and lean requires and promotes a level schedule.

2.2 Overview of Six Sigma Methodology

Many companies use this methodology to achieve competitiveness. Six sigma methodology is used to improve the quality of the product and process dramatically. Sigma, σ, is a letter of the Greek alphabet that is employed to measure the process variability and the sigma level is measured to determine the performance of the business processes (Pyzdek, 2003).The six sigma methodology was introduced by Motorola (1980) and resulted in the accomplishment of business quality in Motorola.

2.2.1 Six Sigma Methodology

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Award. Then, the deployment of six sigma concept is led by Allied-Signal and General Electric (GE).

The six sigma standard of 3.4 problems or defects per million opportunities is used to measure the performance with the 1.5σ shifting that is allowed, as can be shown in Figure 3. Regarding Motorola, small shifts are detected and corrective actions are taken, but below 1.5σ they can go unnoticed over a period. So, in the worst case, the noise factors will cause a process average shift of 1.5σ from the target. Therefore only 4.5σ will be the distance between the new average process and the closest special limit and correspondence to 3.4 DPMO (Bass, 2007).

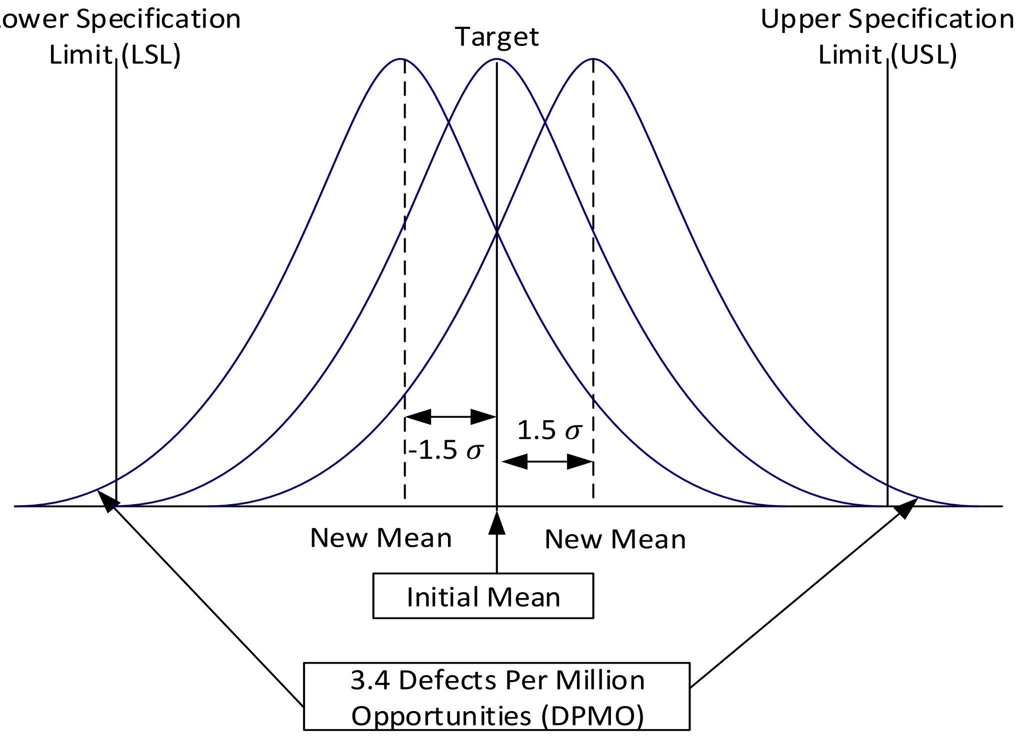


Figure 3.Normal curves of six sigma concept with 1.5σ shifting (Bass, 2007)

Besterfield (2003) states that six sigma is simply a total quality management (TQM) process that uses the process capability analysis as a method of measuring progress. Pyzdek (2003) mentions that six sigma consistently meets or exceeds customer expectations and requirements. Myerson (2012) adds that TQM has seven tools, namely continuous improvement, six sigma, benchmarking, employee empowerment, Taguchi concepts, Just in Time (JIT), and knowledge of TQM tools. Usually, the six sigma methodology is performed by the project team. The company selects members of the team.

Six sigma methodology requires two skills in application, technical and managerial skills, and can be implemented in manufacturing or services companies. The six sigma methodology was initially focused on process improvement and the universally adopted DMAIC approach;

then it was applied to design the product or process stages (Tjahjono et al., 2010). The involvement of top management is needed for selection of the project; otherwise, there will always be a chance of selecting the wrong project, that will have no meaningful impact (Ray and Das, 2010). Pande and Holpp (2002) cite that six sigma methodologies are adopted to improve work processes, speed, efficiencies, profitability, and customer satisfaction.

Six sigma methodology needs defining steps to apply it systematically and these steps can be used to run the projects. Pande et al.(2000) report on the five-phase improvement cycle that has become increasingly common in six sigma organization: Define, Measure, Analyze, Improve, and Control (DMAIC), which is grounded in the original PDCA (Plan-Do-Check-Action) cycle. The PDCA cycle originally came from the Deming cycle that was developed from the Shewhart cycle. Deming (2000) explained that the Shewhart cycle can be useful as a procedure at each stage of improvement and to detect a special cause statistically. Tools applied in the six sigma methodology include statistical process control (SPC), process capability indices, and cost of poor quality (COPQ). Also, other six sigma tools such as quality function deployment (QFD), failure mode effect and analysis (FMEA), and design of experiment (DOE) are often employed. Juran and Godfrey (1999) indicate that six sigma mainly focuses on cost reduction, waste reduction, yield improvements, capacity increases, and cycle-time reduction. These companies also establish clear performance metrics for each improvement in costs, quality, yields, and capacity improvements.

Six sigma is a part of total quality management (TQM) for improving a process or product. Six sigma is a new breakthrough in quality improvement. TQM is a management philosophy that encourages cost reductions, customer satisfaction, high-quality goods and services, employee empowerment, and the measurement of results (Gunasekaran and McGaughey, 2003). Six sigma focuses on reducing excess process variability and poor process centring, so the degree of a defect becomes minimum or zero. Pyzdek (2003) declares that six sigma involves the reduction of process variation to a minimum so that processes permanently meet or exceed customer expectations and requirements. Six sigma uses statistical tools for improving the quality and uses this value as a standard for the industry’s performance and business strategy. Measurements of the sigma value and the process capability indices as baseline performance are required to determine the performance of the current process. After improvements, the sigma value and capability process indices are measured again to monitor the increase of performance.

The sigma value is the measurement to assess the performance of the process and the results of improvement efforts, as a way to measure the quality, and it is used by the business to measure the quality of control of any process to meet the performance standard (McCarty et al., 2004). Pande et al. (2000) discuss the difference between “discrete” (or “attribute”) and “continuous” measures, which is important because it can have an impact on the measurement definition and data collection. Continuous measurements are those factors that can be measured on a definitely divisible scale or continuum, e.g. weight, height, time, etc., whereas a discrete measurement is anything that does not fit the criteria for continuous measures, e.g. the number of orders processed, the level of education, rating a record, etc.

Pyzdek (2003) points out that process capability analysis is in two stages: 1) bringing a process into a state that is controlled statistically in a period; 2) comparing a long-term process performance to management or engineering requirements that require an action. Process capability indices can be calculated if the process is under control statistically. Some examples of process capability indices are Cp and Cpk. Pearn et al.(2004) emphasize that process capability indices are a powerful tool to measure the process performance practically. Kane (1986) defines that the Cp index potentially measures the process performance by the process spread related to the specification limits, while the Cpk index actually measures the process performance by mean measurement of the process. Kane (1986) formulated Cp and Cpk as follows:

$$\mathrm{Cp} = \frac{\text{allowable process spread}}{\text{actual process spread}} = \frac{\mathrm{USL}-\mathrm{LSL}}{6\sigma} \tag{2.1}$$

$$\mathrm{Cpk} = \min(\mathrm{CPU}, \mathrm{CPL}) \tag{2.2}$$

$$\mathrm{CPU} = \frac{\mathrm{USL}-\mu}{3\sigma} \text{ and } \mathrm{CPL} = \frac{\mu-\mathrm{LSL}}{3\sigma} \tag{2.3}$$

where:

USL = Upper specification limit, σ = Natural tolerance
LSL = Lower specification limit, μ = Process mean

Montgomery (2005) stated that there are two reasons causing poor process capability: a) poor process centring, and b) excess process variability, as shown in Figure 4:

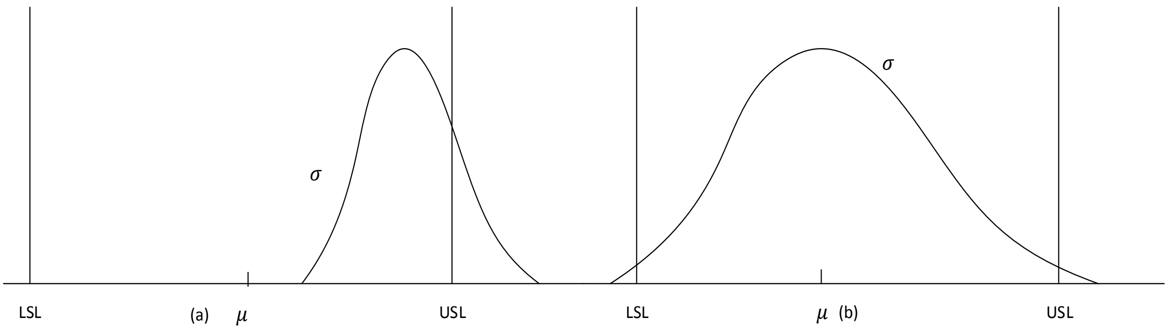


Figure 4.Reasons for poor process capability: a) poor process centring; b) excess process variability (Montgomery, 2001)

The cost of poor quality (COPQ) is analyzed to determine the poor quality of the product or service process that influences the cost. The COPQ must be eliminated to become competitive. COPQ evaluation is one of the fourteen steps of the quality improvement program (Crosby, 1979). Some definitions of COPQ have been given by authors. Sörqvist (2001) in Thomasson and Wallin (2013) defines COPQ as *…"the costs that would be eliminated if a company's products and the processes in its business were perfect".* Hansen and Mowen (2006) define COPQ as *…"the costs that exist because poor quality may or does exist".* Moreover, Schiffauerova and Thomson (2006) defined COPQ as … "*costs incurred in design, implementation, operation and maintenance of a quality management system; resources committed to continuous improvement; product and service failures; and all other necessary costs and non-value added activities required to achieve a quality product or service".* Management can take preventive and corrective actions when the COPQ is high. Gryna in Juran and Godfrey (1999) reveals that the COPQ is identified and analyzed for three reasons: 1) to quantify the size of the quality problem to help justify an improvement effort; 2) to guide the development of that effort; and 3) to track progress in improvement activities. The COPQ is in the range of 10 to 30% of sales or 25 to 40% of operating expenses.

According to Harrington (1999), many researchers have focused on the COPQ since 1943. Firstly, Feigenbaum, CEO of General Systems Co., introduces the cost of quality concept and divides it into four categories, namely prevention cost, appraisal cost, internal defect cost, and external defect cost (the P-A-F model). Later, Philip Crosby categorizes the cost of quality, i.e. rework cost, scrap cost, warranty cost, and quality control labour, and then this is developed into two categories in 1979, i.e. conformance and non-conformance costs, which are called Crosby's Model. Schiffauerova and Thomson (2006) add the opportunity cost and this is discussed by some researchers such as Carr (1992) and Sandoval-Chávez and Beruvides (1998).

Hansen and Mowen (2006) divided COPQ into two categories based on the following activities:

1. **Control activities**: aiming to prevent or detect poor quality that may exist. The control activities consist of prevention and appraisal activities.
2. **Failure activities**: aiming to respond to the poor quality that exists. The failure activities consist of internal failure and external failure activities. Internal failure activities occur before the product or service is delivered to the customer, and external activities occur after the product or service is delivered to the customer.

Regarding these activities, most researchers classified the COPQ into four groups, including Gryna in Juran and Godfrey (1999); Tsai (1998) in Kiani, Shirouyehzad, Bafti and Fouladgar (2009); Sower, Quarles and Broussard (2007); Ramudhin, Alzaman and Bulgak (2008); Hansen and Mowen (2006):

1. **Prevention costs**

   Costs are involved in preventing the poor quality of products and services. Costs are incurred to keep failure and appraisal costs to a minimum. Examples: recruiting, quality audit, quality training, marketing research, quality engineering, quality planning, quality reporting, design review, and many more.

2. **Appraisal costs**

   Costs are involved in making sure the products or services conform to the quality standard, the performance requirements, and the customer needs. Costs are incurred to determine the degree of conformance to quality. Examples: supervising appraisal activities, inspection of equipment, inspection of material, product acceptance, process acceptance, and so on.

3. **Internal failure cost**

   Costs are incurred because the products and services do not conform to the specification and requirement before the products or services are delivered to the customer, such as costs of deficiencies discovered before delivery that are associated with failure.

   Examples: scrap, rework, repairs, downtime, and so on.

4. **External failure cost**

   Costs are incurred because the products and services do not conform to the specifications and requirement of the products or services that are delivered to the customer, such as the cost of deficiencies that are found in the products or services received by the customer.

   Examples: lost sales, warranties, recalls, complaint adjustment, discount due to defect, and many more.

Feigenbaum's P-A-F (Prevention-Appraisal-Failure) model is a COPQ model with a popular name. Investment in prevention and appraisal activities can reduce the failure costs and the investment in prevention activities can also cut the appraisal cost (Porter and Rayner, 1992). Therefore, the target of the COPQ model is to minimize or optimize the cost; thus it is necessary to understand the interaction between the cost elements. Crosby (1979) states that COPQ is not an absolute performance measurement, but an indication to take a corrective action for the company if the COPQ is high.

The failure cost cannot be reduced to zero because this will require higher, usually almost infinite appraisal and prevention cost. Industries intend to get the minimum failure cost but expand the prevention and appraisal cost to an appropriate level. So, the quality level is optimum where the sum of prevention, appraisal, and failure costs is at a minimum, as can be seen in Figure 5 (a). The new model of optimum quality cost is shown in Figure 5 (b). This model consolidates the possibility of zero defects by recognizing the root causes and taking action for the improvement. The new model creates a mindset to get the perfection with many approaches such as six sigma concept, kaizen, reengineering, and other continuous improvement approaches (Gryna in Juran, 1988). Practically, zero defect is difficult to be achieved, hence the optimum quality cost is actually a trade-off between prevention and appraisal cost, and failure cost. This optimum quality level allows the prevention and appraisal costs more than the failure costs as it can be seen in Figure 5 (b). The optimum level of COPQ can refer to the model of Gryna in Juran (1988), as shown in Figure 5:

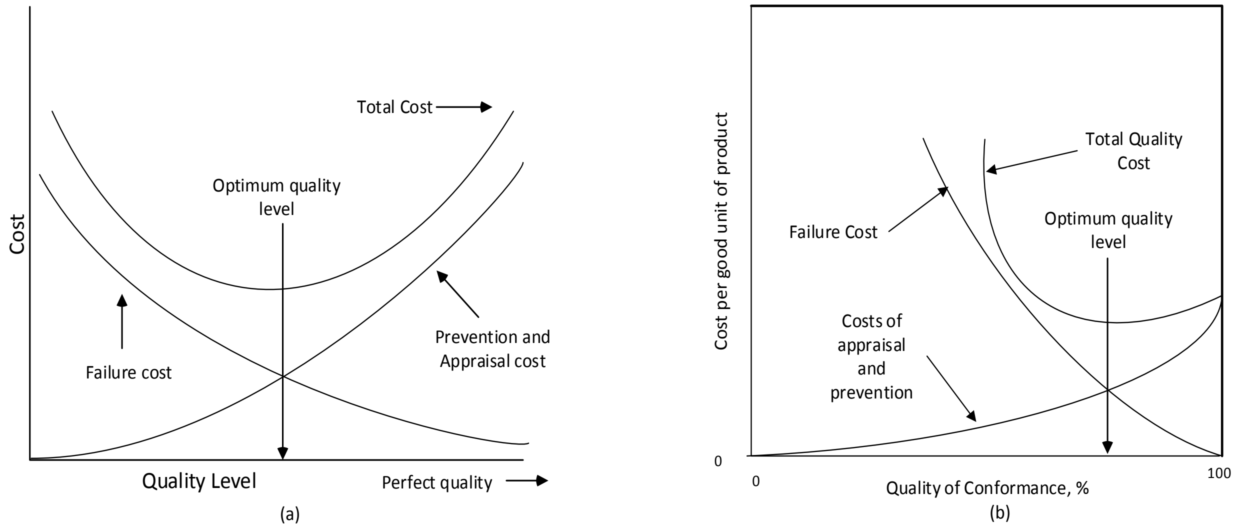


Figure 5.Model for the optimum level of cost of poor quality: a) classical model (Gryna in Juran, 1988); b) new model (modified from Gryna in Juran, 1988)

According to Carr (1992) and Sandoval-Chávez and Beruvides (1998), the loss opportunity cost (or hidden cost) is enhanced for application in the services industry. The loss opportunity costs are influenced by the conformance cost (prevention and appraisal cost) and non-conformance cost (internal and external cost). Schiffauerova and Thomson (2006) reveal that the opportunity or intangible costs are costs that are estimated as a profit but are not earned because of customer loss or reduction in revenue. The calculation of the opportunity cost can be performed by three methods, as follows: (1) the multiplier method, (2) the market research method, and (3) Taguchi's quality loss function (Albright and Roth, 1992, in Hansen and Mowen, 2006).

2.2.2 Lean Six Sigma

Another concept for the process improvement is lean six sigma or lean sigma which is an integration between lean and six sigma concepts. According to Bain and Company (2012) in Myerson (2012), lean manufacturing aims to eliminate waste and six sigma supports companies in decreasing errors. Lean six sigma can support companies to achieve the advantages of the quicker process with the lower cost and higher quality. Bendell (2006) states that lean six sigma or lean sigma is a combination of two process improvement approaches, i.e.: lean thinking and six sigma. Lean thinking focuses on reducing and eliminating the waste with the analyzing of value and process. Six sigma focuses on reducing and eliminating the variation with statistical tools application and supporting software. Higgins (2005) in Pepper and Spedding (2009) mention that six sigma is implemented by a several appointed individuals within a company, but lean stages empower and educate the employee in the organization to recognize and remove non-value added activities. Many companies implement lean six sigma to improve their business and obtain a competitive advantage. Many organizations have adjusted Lean and Six Sigma and used them to fulfill their specific requirements (Oppenheim et al., 2010).

Lean six sigma becomes a methodological approach in improvement strategies and techniques. Sharma (2003) depicts the advantages of utilizing the six sigma techniques in combination with lean, where the objectives of strategic improvement are provided by the leaders of the company. Then, the quality function deployment (QFD) tool is applied to emphasize the project. Also, lean six sigma become a breakthrough concept of the innovations to improve their business performance. The leading companies utilize lean six sigma and they pursue the larger innovation agenda (Byrne et al., 2007). According to Snee (2010), lean six sigma is a methodology and strategy of business that enhances the performance of the process, generating in increasing customer satisfaction and enhanced bottom line results.

Lean six sigma can be used to analyze the root causes of the problem and design the improvements. Martin (2007) proves that lean six sigma methods are effective in investigating the root causes of the problems as well as removing them from the process. Steps for the lean six sigma use the DMAIC (define, measure, analyze, improve, control) cycle to solve the problem. Besseris (2011) states that lean six sigma is a blueprint for any project of improvement to offer a brief method-based approach and concept on how to work with robust decisions on the pathway to product and process.

The success of lean six sigma depends on how lean six sigma works in various areas. Snee (2010) mentions that there are eight key characteristics of lean six sigma, as follows: 1) establishing bottom line results; (2) leadership of active senior management; (3) utilizing a disciplined approach (DMAIC); (4) rapid project accomplishment (three to six months); (5) obvious definition of success; (6) well-developed infrastructure (master black belt, black belt, green belt); (7) concentrating on processes and customers; and (8) using statistical approaches. Lean six sigma works better because it involves human and process aspects for the improvement. For the human aspects, the implementation of the lean six sigma model establishes the culture of continuous improvement and promotes an effective leadership in the organization. For the process aspects, the lean six sigma encourages the company to utilize the statistical techniques in advance and problem solving becoming more "technical" in their method (Thomas et al., 2008).

Process improvements use the lean six sigma idea with performance indicators. Many approaches are used to select the performance indicators. It depends on the improvement area considered. Snee (2010) considers the types of required improvement, containing the requirement to shorten the process flow for decreasing the complexity, decreasing downtime, streamlining cycle time and eliminating waste; improving the quality of product; achieving regularity in the delivery of product; decreasing the process and product costs; reducing the process variation; improving the process control to preserve steady and expected processes; finding the delightful point in the process operating window; and achieving the robustness of process and product. Several metrics come from financial or customer perspectives. For example, Martin (2007) identifies and deploys metrics as a baseline: 1) level of customer service; 2) net profit after taxes (NOPAT); 3) gross profit margin; 4) return-on-asset (ROA); 5) gross-margin-return-on-assets (GMROI); 6) asset efficiency; 7) fixed asset efficiency; 8) account receivables efficiency.

2.3 Overview of Simulation Model using System Dynamics

Simulation models have become a trending topic for describing real systems. A model is a simplification of the real world. According to Pidd (2003), the model is a representation of a part of reality that people wish to understand, change, manage, and control. The simulation is used to determine the behavior of the real system. Forrester (1961) clarifies that the simulation consists of tracing through the flows of orders, goods, and information, then observing the sequences of new decisions. After the behavior of the system is known, then the process simulation can improve the performance of the system. Simulation models should be developed that apply continuous improvement concepts.

2.3.1 System Dynamics (SD)

Simulation using system dynamics (SD) was developed by Forrester (1961) from Massachusetts Institute of Technology (MIT). System dynamics is a computer-aided approach, initially known as “industrial dynamics” (Forrester, 1961), where industrial dynamics is described as: *“…the study of the information feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decision and actions) interact to influence the success of the enterprise”.* System dynamics consists of two main characteristics, i.e. feedback loop structures and delay. Pidd (2003) states that delays and feedback loops are the fundamentals of system dynamics, and are responsible for describing the behavior of the real system. Later, Yeo et al.(2013) mention that system dynamics consists of two factors: the system, which indicates an object to be observed, and the dynamics, which relate to the changes in an object depending on time. System dynamics in a simulation has the advantage of observing the behavior of the system based on the changing of time. According to Forrester (1992), system dynamics (SD) leads to equations of the model, simulation to understanding the dynamic behavior, the evaluation of alternative policies, education, and the choice of a better policy and implementation.

Building a model of system dynamics requires skills in qualitative and quantitative analysis. Pfaffenbichler et al.(2010) mention two key elements of system dynamics (SD) in modeling, i.e. the structure of the modeled system as a qualitative skill and the parameters of the modeled system as a quantitative skill. The simulation model in system dynamics is a stochastic simulation model, so that quantitative skill is required to check the data distribution. There is a major difference between deterministic and stochastic simulation models. The stochastic models describe the behavior when there are random effects and the deterministic models assume that there is no random effect (Shapiro, 2001). Nevertheless, the nature of the system in the real world is impossible to expose by simulation. According to Forrester (1968), simulation is not the core of industrial dynamics because simulation is only a technique that utilizes a mathematical, analytical solution to reveal the nature of system models.

Sterman (2000) states that successful modellers must follow the five steps below:

1. **Articulating the problem to be addressed**;
   The problem can be dynamically defined by the two most useful methods, i.e. establishing reference models and setting the time horizon.
2. **Formulating a dynamic hypothesis concerning the causes of the problem;**
   Techniques and tools have been formulated to create and represent ideas into a dynamic hypothesis. Firstly, endogenous and exogenous variables are determined. The endogenous variable becomes a main point in the system dynamics because it generates the interaction between each component in the system. Meanwhile, the exogenous variable comes from outside the system but influences the system. Sterman (2000) mentions that the number of exogenous variables should be small

and must be considered carefully. Secondly, a model boundary chart is determined by making a list of key variables, both endogenous and exogenous. The model boundary chart is required to decide whether the model is appropriate or not, based on the objective of the model.

Thirdly, a sub-system diagram is built to know the overall description of a model. This diagram explains the hierarchical structure of the main model and creates organizations such as the firm and organizational units such as operations, marketing, etc. Then, the formulation of a dynamic hypothesis uses a causal loop diagram and stock flow diagram. A causal loop diagram is built to describe the relationship between variables and design feedback loop structures in the system. The stock flow diagram is used to control the flow of things accumulating through the system, such as material, money, and information.

3. **Formulating a simulation model to test the dynamic hypothesis**;

   The dynamic hypothesis can be tested directly by data collection or experiments in the real conditions. Many things are required to create a simulation, such as defining parameter inputs, equations, and the initial state. This formulation aims to find and recognize the broad concepts of the conceptual models by generating important keys before the model is simulated.

4. **Testing the model until it is suitable for the purpose**;

   This step is performed to test the responsiveness or sensitivity of the model. Testing is repeatedly done until the model is appropriate for the purpose. The behavior of the model can be analyzed and compared with the real world. To set up a dynamics model for simulating company or industry behavior, the actual system that it represents must be described (Forrester, 1961).

5. **Designing and evaluating policies for improvement**.

   The policy of improvement designs is conducted by not only changing the parameter inputs but also creating new structures including feedback loop structures, new strategies, and decision rules. Sometimes, the new policy design can disturb or reinforce another policy design, so the policy design must be evaluated.

The causal loop diagram (CLD) is one of the tools for formulating a dynamics hypothesis and is widely applied to describe the behavior of a system by analyzing the causalities between variables, including the feedback loop structure. The components of the CLD are variables and arrows that represent the causalities between variables. This hub is also called a causal link that should assign positive (+) and negative (-) polarity. Sterman (2000) mentions that the positive link means that if the cause increases, the effect increases, and if the cause decreases, the effect decreases, while a negative link means that if the cause increases, the effect decreases and if the cause decreases, the effect increases. The link polarity shows the structure of the system and what will happen if there are changes.

The stock flow diagram (SFD) is built after the causal loop diagram (CLD). The SFD can complement the CLD by capturing the stock and flow structure. The stock flow diagram concept originated by Forrester in 1961, based on a hydraulic metaphor – the flow of water into and out of reservoirs, as shown in Figure 6. The quantity of water in the bathtub at any time is the accumulation of the water flowing in through the tap less the water flowing out through the drain (Sterman, 2000).

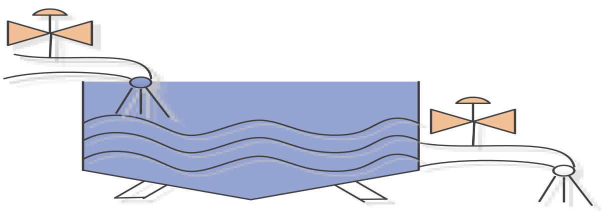
Integral equation:

$$\text{Stock (t)} = \int_{to}^{t}[\text{Inflow(s)} - \text{Outflow (s)}]ds + \text{Stock (to)} \tag{2.4}$$

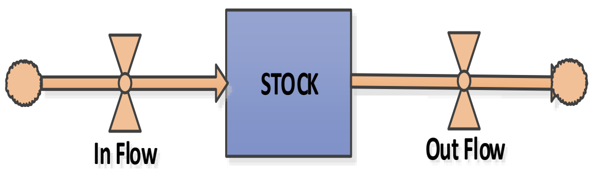
Where Inflow (s) represents the value of the inflow any time s between the initial time to and the current time t.

Differential equation:

$$\frac{d(\text{Stock})}{dt} = \text{Net Change in Stock} = \text{Inflow (t)} - \text{Outflow(t)} \tag{2.5}$$



1) Hydraulic Metaphor



2) Stock and Flow Diagram

Figure 6.Stock and flow diagram concept (Sterman, 2000)

From Figure 6, the stock is created by the accumulation of the differences between inflow and outflow that make the stock become the source of a disequilibrium dynamic in the system. Furthermore, the stock characterizes the state of the system and becomes a fundamental for actions.

Another important thing in building the SFD is putting in a feedback loop structure from the stock. Kampmann (2012) states that the feedback loop will connect every pair of state variables so that the system dynamics model will be strongly connected. Sterman (2000) states that the two types of feedback loop structures in system dynamics, positive and negative. Firstly, the positive feedback loop structure leads the state of the system to start increasing, as shown in Figure 7. The state of the system accumulates the net inflow rate and the net inflow rate depends on the state of the system.

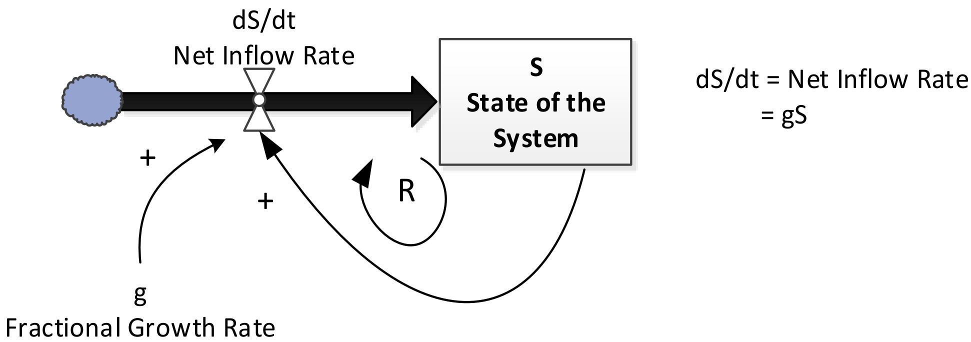


Figure 7.Positive feedback loop (Sterman, 2000)

Meanwhile, the negative feedback loop structure leads to the state of the system decreasing as shown in Figure 8. Increasing the state of the system will magnify the value of the decay rate so that the state of the system will remain at zero or a desired goal.

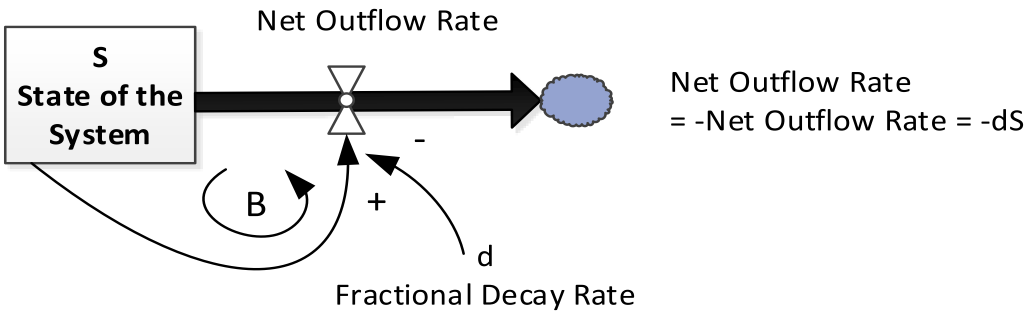


Figure 8.Negative feedback loop (Sterman, 2000)

System thinking is a way to understand and analyze the real system in the world. Systems in the world are complex problems so that it is needed the system thinking concepts. Forrester (2007) mentioned that system thinking is the first step to build System Dynamics from the complex problems. Then, system thinking can generate a conceptual model that is developed to describe the real system so that the whole system could be known. Yuan and Wang (2014) states there are two major steps for developing System Dynamics (SD): 1) conceptual model that describes the real system from a qualitative point of view; 2) formal

System Dynamics (SD) that formulated based on a conceptual model of professional software package to simulate quantitatively the model and analyze the results of the simulation. Therefore, it is required to build a conceptual model for our system. A case study is needed to prove the conceptual model. Regarding Sterman (2000), conceptualization of case study: 1) problem definition; 2) identification of key variables; 3) developing the reference model; 4) developing the causal diagram.

Regarding Forrester (1968), the behavior structure in the model system represents the interaction between any systems. That means, the variables of the system must be considered how they are interacting with each other so that the system has a definite behavior. Sterman (2000) mentions the fundamental modes of the dynamic behavior as depicted in Figure 9 below:

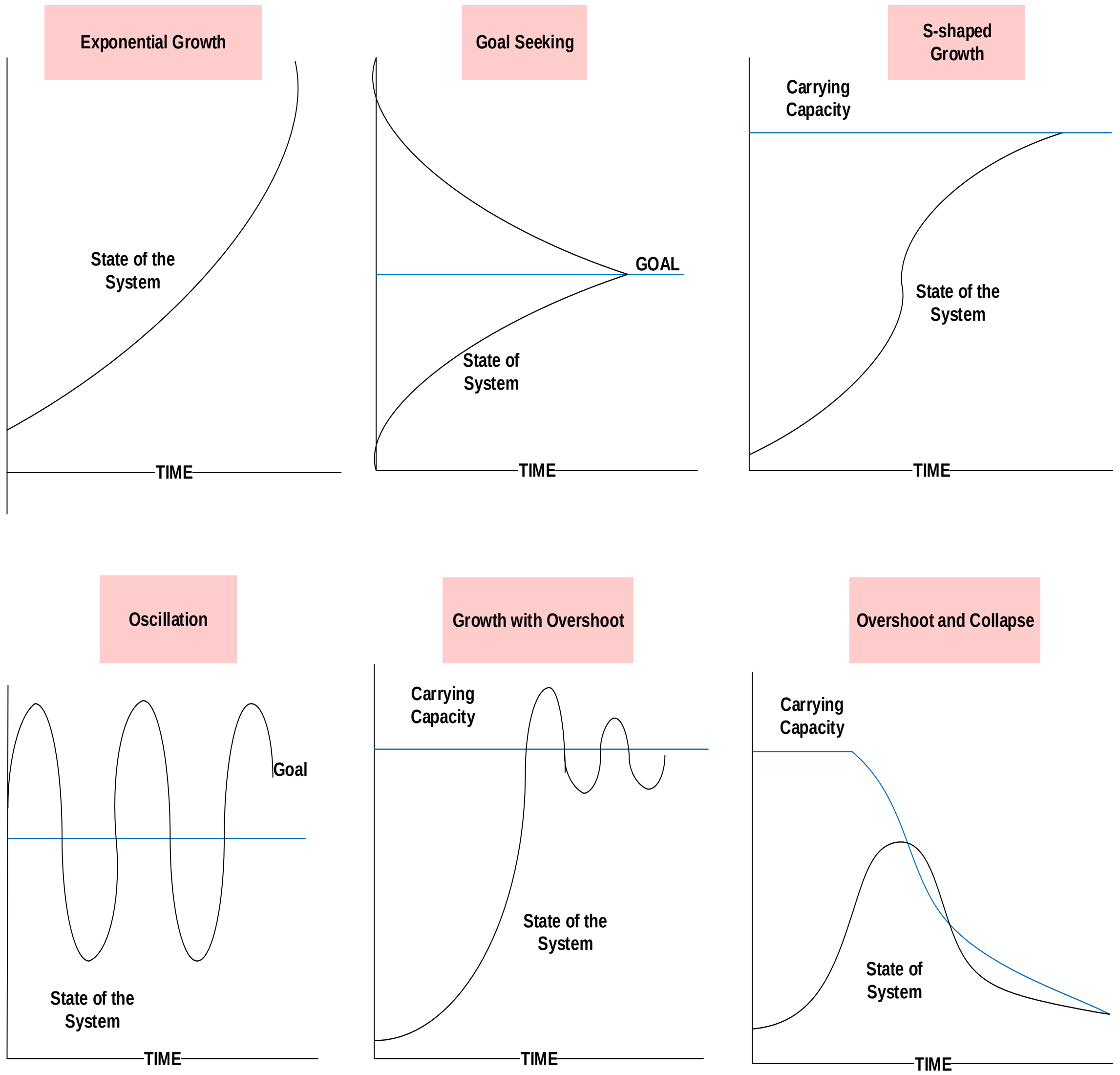


Figure 9.Common models of behavior in dynamic systems (Sterman, 2000)

From the figure above, the common behaviors of models in dynamic systems are explained as follows:

1. **Exponential growth**

   Exponential growth occurs because of the positive feedback loop structure. The increasing values depend on the state of the system. The initial value of a stock begins to increase and then the growth rate also increases. Each component in the system reinforces each other. The state of the system increases the net increase rate, and the net increase rate will add to the state of the system. Population growth because of the birth rate is one example of such behavior.

2. **Goal seeking**

   This behavior happens when there is a discrepancy between the actual and the desired value. The behavior of goal seeking appears due to the negative feedback loop structure. Sometimes the desired state of the system and the corrective action are explicit; this means that a decision maker controls this condition. The generation of the defect rate in the manufacturing process forms a goal seeking behavior. The process improvement program has the goal of zero defects and develops the behavior of goal seeking.

3. **S-shaped growth**

   This behavior commonly occurs in dynamic systems. The interaction of positive and negative loops generates the structure of the behavior of S-shaped growth, and the interaction must be non-linear. This behavior happens if two conditions are fulfilled: the negative loops are without significant time delays and the carrying capacity is fixed. The behavior occurs first in an exponential growth, and then the state of the system will achieve the value of equilibrium slowly. The growth of a plant or new product generates S-shaped growth behavior.

4. **Oscillation**

   This type of behavior is caused by the negative feedback loops. The state of the system will try to achieve the desired goal due to the discrepancy between the actual and desired goal. Because of the time delays, corrective actions to reduce the discrepancy will continue until the state of the system reaches its goal, until when the state of the system fluctuates around the value of the desired goal. A specific characteristic that occurs in oscillation is the existence of overshooting and undershooting due to significant time delays in the negative feedback loop structure. The time delay creates a new corrective action in the opposite direction. The oscillation behavior usually occurs in dynamic systems. The inventory level is an example of oscillation behavior that needs time delays.

5. **Growth with overshoot**

In many cases, conditions will be found where time delays exist along with positive feedback loop structures and negative feedback loop structures. A system having time delays in the negative feedback loop structure will develop the S-shaped behavior with overshoot and oscillate around the carrying capacity. The population growth will generate this behavior until reaching equilibrium.

6. **Overshoot and collapse**

   This behavior begins with an exponential growth, then reaches its maximum. Unlike S-shaped growth, the system does not reach equilibrium but the state of the system declines. For example, the number of deer in a forest can grow so large that they eat all the grass, causing starvation and a steep decline in the population.

One important thing needed to build a successful model is validation. Testing of the model until fit for the purpose is required to ensure that the model is valid. Barlas (1996) states that the validation of a system dynamics model is more complicated than a black-box model, because judging the validity of the model structure is very problematic, both philosophically and technically. Also, Forrester (1968) mentions several major defects in the mental models of system dynamics: 1) mental models are ill-defined; 2) assumptions are not identified clearly in the mental model; 3) the mental model is not easy to communicate to others; 4) mental models of dynamic systems cannot be manipulated effectively. Testing is performed to accommodate all variables that are related to the model. Sterman (2000) states that two aspects are to be considered in the testing; first, each question must have dimensional consistency and second, the model must be able to be run under extreme conditions.

Statistical methods are used to make sure the testing is acceptable. The two-sample t-test and Analysis of Variance (ANOVA) is a common statistical method that is often used to test the result of a model simulation and compare it with the real data. Ott and Longnecker (2001) mention two-sample t-test is utilized to validate the equality of two populations that have normal distributions. The t is calculated by comparing between the sample means and the variance of two sets of data of size, n. The critical t-value is determined by t table based on the degree of freedom, df, and degree of confidence, α. The result of the model simulation and the real data are the same significantly when t-value ≤ critical t-value. Burke (1987) states that ANOVA is an applicator to check and analyze results from two or more data sets at the same time. ANOVA is calculated by comparing between the groups variance and the error variance to get the value of F. Also, the critical F-value is determined by an F table based on the degree of freedom, df, and degree of confidence, α. The result of the model simulation and the real data are the same significantly when F value ≤ critical F-value.

The design of the policy of improvement scenarios is established after the model is validated. These scenarios will ensure that the model is useful, and the performance of the system will be improved. Suryani et al.(2010) note that the two kinds of scenario in the simulation are the parameter scenario, which means that the scenario is made by changing a parameter value, and the structure scenario, where the scenario is made by adding some feedback loops, adding new parameters, or changing the structure of the feedback loops. Meanwhile, Sterman (2000) states that the policy of improvement scenarios is not only by changing the input parameters but also by creating new structures, new strategies, and decision rules. The robustness and sensitivity of the new policy of improvement scenarios are required to appraise the model in conditions of uncertainty. The interaction between scenarios can cause them to disturb one another.

2.3.2 Supply Chain Management (SCM) and System Dynamics (SD)

The implementation of system dynamics in supply chain management cannot be separated from the model of the production-distribution system in Forrester (1961). The model comprises six interacting flow systems, i.e.: 1) materials; 2) orders; 3) money; 4) personnel; 5) capital equipment; and 6) information. Through system dynamics, Forrester assesses the causal relationship among the variables within supply chain management. Sterman (1989), in Angerhofer and Angelides (2000), applied the 'beer game' to perform an experiment on executing a simulation of the industrial production and distribution system. The beer game provides a multi-echelon production distribution system, including multiple actors, non-linearity, time delays and feedbacks along the supply line. The players are guided to decrease costs by arranging their inventories based on the uncertainty demand and unknown delivery. From this game, it is known that the bullwhip effect will occur as the impact of the demand uncertainty and lack of coordination between the actors.

Applying the system dynamics model in supply chain management enables the assessment of the causal relationships between players in the supply chain. Also, this applying enables the solution of the problems in the entire supply chain and gives opportunities for improvement. Anderson et al. (1997) provide a system dynamics simulation model to assess demand variability amplification in the supply chain with the exploring lead-time, production, inventory, productivity, and staffing involvement of these dynamic coercions. Lee et al.(1997) in Anderson et al. (1997) develop the model of bullwhip effect that will occur if any of the following conditions are not met, i.e.: 1) demand is stable; 2) resupply is unlimited with a constant lead time; 3) there is no permanent order cost; and 4) the purchase cost of the product is balanced over time. Barlas and Aksogan (1997) in Angerhofer and Angelides (2000), utilize a case study in the apparel industry to design a system dynamics simulation model of a distinctive retail supply chain, involving a three echelon chain, i.e.: manufacturer, wholesaler, retailer and end user. The objective of their simulation is to construct inventory policies that may increase the retailer’s revenue and decrease costs at the same time.

Giogiadis et al. (2005) implement a system dynamics simulation model for the planning process of the transportation capacity in the supply chain of fast-food restaurant. Capacity may designate to all operations of a supply chain, e.g. manpower, stock space, transportation means, production facilities, etc.

System dynamics is a suitable tool for modeling the supply chain and designing the policy improvements. Sterman (2000) states that the effective models must reflect different actors and organizations, incorporating suppliers, the company, distribution channels, and customers. They involve multiple chains of stocks and flows, time delays, and feedbacks loop between the partners in a supply chain. Giorgiadis et al. (2005) mention that system dynamics approach can extend multi-echelon supply chains and enhance issues of the strategic supply chain management. After developing and simulating the model, the performance of supply chain can be improved by designing the policy improvement scenarios. Now, system dynamics are required to improve the performance of supply chain as a system. Akkermans and Dellaert (2005) states the complex dynamics that establish the performance of supply chains becomes vital for excellent performance in supply chain management.

Several types of model have been used to represent the real system in the supply chain. Shapiro (2001) mentions that there are two types of model, i.e.: 1) descriptive models; and 2) normative models. Descriptive models develop functional relationships in the company and the external world, including: 1) forecasting models; 2) relationships of cost; 3) relationships of resource utilization; and 4) simulation models. Normative models assist managers in the decision-making process. The term normative points to the processes for recognizing norms that the company should attempt to achieve. Normative models are synonyms with optimization models. The construction of optimization models requires descriptive data and models as inputs. Many model implementation project passes through several stages of data and model validation until sufficient accuracy is achieved.

Supply chain management relates to managing all functions as an integrated approach. Shapiro (2001) addresses supply chain management with functional integration of manufacturing, purchasing, warehousing, and transportation activities. Eventually, functional integration of these activities is achieved including the perspectives of strategic, tactical, and operational planning. Sterman (2000) mentions that the objective of a supply chain is to serve the right output at the right time. As customer needs change, the managers of the supply chain respond by modifying the rate at which resources are reserved and used. Supply chains are thus ruled primarily by negative feedback. Because supply chains typically include significant time delays, they are liable to oscillation-production and inventories chronically undershoot and overshoot the suitable levels. The common structure is responsible for oscillations: negative feedbacks with time delays. In each negative loop, the state of the system is matched to the desired state and any discrepancy that leads to a corrective action. When there are no time delays, the corrective actions react immediately to the discrepancy and change the state of the system. In equilibrium, average orders now will be equal to the actual orders, orders will be similar to delivery, and inventory will be equivalent to the desired level.

2.4 Overview of the Port as Industry

The port is an important means of opening access to trading with other countries or other regions in a country. The term port comes from the Latin word “Portus”, which means gate or gateway. A port’s function is to serve ships and to give access to navigable water. Maritime operations are among the most crucial transactions in global business today intertwining multi-various specializations associated with numerous trades including shipbuilding, chartering and the freight transport of bulk products, containers, fuel and even people. According to Rodrigue et al.(2006), three important corridors in waterway logistics have to be considered: 1) maritime access, referring to the physical capacity of the site to accommodate ship operations; 2) maritime interface, indicating the amount of space that is available to support maritime access, namely the amount of shoreline that has good maritime access; 3) land access, from the port to industrial complexes and markets, ensuring its growth and importance.

Panayides and Song (2013) states that maritime logistics is related to the planning process, implementing, and arranging the movement of goods and information in the ocean transport. There are three maritime logistics activities:

a. Shipping:
   Moving goods of shippers from one port to another. Also, it provides logistics services to successfully support the shipping and logistics flow, e.g.: pick up service, shipment notification, container tracking, etc.
b. Port/Terminal operation
   Loading/unloading cargoes into/from a vessel and making preparations for the cargoes to be delivered to the final destination through inland transportation. Modern logistics system includes diverse value-adding services including storage, warehousing, and packing and organizing inland transportation modes.
c. Freight forwarding
   Reserving a vessel on behalf of shippers, or set up the requirement documents for ocean transport (e.g. bill of lading, B/L) and other documents needed for customs clearance and/or insurance needs.

Maritime logistics includes the service in sea transportation as well as extra logistics service e.g. materials handling, warehousing, industrial packaging, distribution planning, finished goods inventory, transportation, order processing, and customer service. Entire logistics chain involves:

1. Material management: purchasing, demand forecasting, production planning, requirement planning, manufacturing inventory.
2. Physical distribution: distribution planning, finished goods inventory, order processing, transportation, and customer service.

According to Alderton (2008), many ports are taking benefit of their strategic position in the logistics chain by the contribution of numerous additional value-added services. These not only add value to the cargo they manage but can also greatly rise the profitability of the port. They can involve not only the traditional port storage facilities but may also involve arranging such services as distribution and market preparation centers.

2.4.1 Port Terminals

According to Ligteringen and Velsink (2012), there are ten main types of terminals that can be differentiated as follows:

1. Conventional general cargo terminal
   This terminal is traditionally constructed for handling of break bulk and unitized general cargo. A modern general cargo terminal must be able to manage a much greater diversity of cargo, including containers brought on deck of multi-purpose vessels, at a much greater speed.
2. Multi-purpose terminal
   Most multi-purpose terminals merge conventional break-bulk with container and/or Ro/Ro cargo. The containers are not irregular anymor, but part of the usual cargo flow for which specialized equipment is available.
3. Ro-Ro terminal
   This terminal is appropriate for ships with quarter and/or side ramps at marginal quay. It provided that there are no barriers like bollards and rails. This terminal shows a great diversity of landside layouts, relating on how much parking area is required for the trailers.
4. Container terminal
   The storage of containers on the terminal often occurs for several days until several weeks. Container terminals can be easily recognized as large areas with the piles either parallel with or normal to the waterfront. Another characteristic of modern

container terminals is the huge cranes with their stake in upright position, when inactive.

5. Liquid bulk terminal

   Whether for oil, chemicals or liquid gas, all of these terminals have one thing in common: the ship is unloaded via a central manifold and it is not required for heavy cranes shifting alongside.

6. Dry bulk terminal

   This terminal is often constructed and built for one specific type of cargo, e.g.: iron ore, coal, fertilizer, grain, etc. The loading of bulk carriers in the export terminal is performed by conveyor belts, extending right above the ship, from which the material falls freely into the holds at fixed and high capacity. At the import terminal, the same cargo is unloaded by cranes, which must be able to move around in order to recover all the material within the hold and to move from one hold to another.

7. Fruit terminal

   Modern fruit terminals are distinguished by refrigerated warehouses that are placed near the waterfront. In some ports, the cargo is moved directly from the ship into the warehouse by conveyor belts.

8. Fish handling facilities

   As fishing ports may differ from a simple beach arrival to a standard harbor, the facilities also exhibit a large variation. The minimum requirement for a harbor is a refrigerated shed for the storage of the captured fishes.

9. Inland barge terminal

   Similar like the seaports, the layout of barge terminals relies on the type of handled cargo. This may differ from multi-purpose/container to bulk cargo and the features are alike to those of the seaport terminals.

10. Ferry and cruise terminal

    The passenger ferry and cruise terminal is focused on the rapid and secure movement of passengers. Passenger ferries and cruise terminals need a terminal building like a railway station, with ticket counters, waiting lounges, shops, restaurants, and rest rooms.

Tsinker (1997) stated that the development of the modern port is linked with the whole transportation system to optimize the total network. All transportation modes are very important to deliver the cargo to the destination warehouse. Warehouses in port have a function as buffer to keep the cargo temporarily. Some cargoes are delivered from berths to the destination warehouse directly. The rate of deliveries to end clients and the speed of loading and unloading processes in dry bulk port terminals can be independent due to the function of this buffer (van Vianen et al., 2012). Ligteringen and Velsink (2012) mention that the import or unloading terminals are much more different, both in location, size, and cargo handling system. The export-loading terminals are usually placed as close as possible to the source or the good connection of rail to the source (Alderton, 2014).

Bulk cargos consist of large homogeneous quantities of unpacked cargo, for instance, liquids (oil, liquefied gas), chemical products (phosphate, fertilizer), agro products (grain, rice, etc.), cement, coal, and iron ore. The various methods of bulk cargo handling can be performed by pumping (liquids), slurrying, sucking (cereals), a combination of grabs and a conveyor belt system (coal and ores), and a mixture of dry bulk cargo and liquid (pipeline). The dry bulk vessels are designed to bring uniform large quantities of bulk cargos such as grain, coal, ore, etc. Dry bulk cargoes can be grouped into: 1) major bulk, e.g. iron ore, grain, coal, phosphate, bauxite; 2) minor bulk, e.g. sugar, bentonite, rice, gypsum, wood shaving & chips, salt, fish, copra. Dry bulk cargo is delivered mostly in lax form, which establishes to a major level the transport technology employed at the berths and the terminal. According to the large quantities often handled in these ports, extensive storage facilities are needed and the requisite land area must be available.

The equipment and transporters for cargo-handling process are designed to support the activities in ports. Capacity of the equipment and transporters has been considered in designing the port terminals. According to Layaa and Dullaert in Notteboom (2011) there are three capacity level in ports as follows: 1) design capacity, relates to the theoretical output of a process; 2) effective capacity, decreased by planned factors such as preventive maintenance, training and set up times, etc.; 3) actual capacity, decreased by planned factors and unplanned activities e.g.: unexpected machine breakdowns, worker absenteeism, weather conditions, etc. Alderton (2014) mentions that there are three definitions of capacity in dry bulk terminals: 1) peak capacity, the maximum unloading rate under total optimum conditions; 2) rated capacity, the unloading rate based on the cycle time of a full bucket or grab from the digging point inside the vessel to the receiving hopper on the berths; 3) effective capacity, the average hourly rate achieved during the unloading of the entire cargo of a ship.

2.4.2 Port Performance

Port management try to improve the performance so that it becomes an attractive port and could be competitive. Yeo et al. (2008) states that key factors for port competitiveness have changed away from hardware and labor towards software and technology, signifying that the most competitive ports depend on efficient hinterland. Tongzon and Heng (2005) mention that private sector involvement in the port industry is helpful for improving port operation efficiency. The operation efficiency is very significant for port authorities and port operators to obtain a competitive advantage, implying that partial port privatization is a merely effective way to assist port authorities to win in the competition. It will encourage port management measures the port performance to establish how knowledge has been applied in an efficient and effective way (Marlow and Casaca, 2003).

The attractiveness of port becomes a target to meet the customer requirements. According to Hu and Lee (2011), the top five quality attributes that customers are not satisfied with are: port congestion; inappropriate completion of accident claims; lower clearness in pricing negotiation and administrative process; lack of monitoring system for the customer satisfaction on the port services; and low level service of cargo claims and of port customer’s requirement. Several researchers implement the improvements to enhance the port productivity. Paixão and Marlow (2003) state the agility of the port is also relevant in competing efficiently in the competitive environment. This agility clarifies the significance of the port in the international environment; the level of competition at the port has been increasing for the last few years, and no longer competes on cost alone, but also on the quality of transport services. Also, the competitive environment involves uncertainty about the future, the phenomenon of globalization, the important organizational and commercial technology evolution that is taking place in the transport sector, and fast communication systems. Bae et al. (2013) design the two-stage duopoly model of container port competition for transshipment cargoes. Caballini et al. (2012) explain that an integrated systems approach, both technological and organizational, is essential to increase the efficiency of the rail port cycle, enhancing the flow of goods transferred by rail.

The port performance indicators consist of the service indicators and the utilization indicators. The service indicators involve the operation time and availability of infrastructures, while the utilization indicators consist of the berth occupancy and the storage utilization. According to Thoresen (2014), port management have three options for reducing the waiting time that relate to the operation time, i.e.: 1) increasing the number of berths; 2) increasing the working time at the berths; 3) improving the productivity of the terminal cargo-handling. The number of berths needed in a port depends on many factors such as demand, size, and type of ship, etc. According to Alderton (2008), a great level tries to improve the port productivity with reducing either the ship time in port or reducing costs. The berth occupancy ratio (BOR) is one of the utilization indicators to improve the port productivity. This is the ratio gained by dividing the time a berth (or group of berths) has been occupied by the time the berth (or group of berths) is available during definite period of time. Some ports will utilize the service time, which is usually the total actual time of the vessel is berthed, while other ports may include only the working time. Service time is the period of time during which a vessel is berthed in a port. The service time will involve working and nonworking periods. Waiting time is the time a vessel is waiting for an available berth. Dwell time is the time spent by the container in the port. Port congestion or waiting time appears when port capacity is not sufficient to overcome the traffic at the port.

According to Thoresen (2014), the number of berths influences the BOR value. From the Table 1, when there are 6 berths or more, the BOR is 70% on average, but the BOR should be less than 70% to achieve high berth utilization and avoid the congestion that causes the vessel waiting time to increase.

Table 1.Berth occupancy (Thoresen, 2014)

Number of berths	Control of arrival vessel to berths		
	None	Average	High
1	25 %	35 %	45 %
2	40 %	45 %	50 %
3	45%	50 %	55 %
4	55 %	60 %	65 %
5	60 %	65 %	70 %
6 or more	65 %	70 %	75 %

The actual BOR will rely on the port administration's control of the ship arrivals at the berths. For oil and gas berths, a satisfactory BOR for two berths is 60%. High berth occupancy factors might seem attractive because they result in the highest berth utilization, but it is common to assume a ratio of the average vessel waiting time to the average vessel service time not higher than 5–20%. The berth occupancy time will also rely on the type of berth, the type and size of vessel, transfer equipment, environmental conditions, etc.

The value of BOR for a general-purpose berth is around 0.7. If the ratio is too large the port is facing the critical possibility of congestion. On the other hand, if the ratio is too small the management could face the criticism of over-investment. Takel (1970) in Thoresen (2014) describes an average berth utilization factor of 0.46 or 46% and that Le Havre allows its berth utilization factor of 67% too high and promptly decided to design six extra berths, which it estimated to bring the berth utilization factor down to around 57%.

Chapter 3

Research Methodology

This research follows the methodology that refers to the development of a system dynamics (SD) model that is integrated with six sigma methodology. The SD model built relates to Sterman (2000) and consists of conceptualization, formulation, validation, and the scenario of simulation, whereas the six sigma methodology refers to Pyzdek (2003), with the improvement model known as the DMAIC process (define, measure, analyze, improve, control).

3.1 Integration of Six Sigma and System Dynamics Model

Integration of the system dynamics and six sigma model is applied to improve the lean supply chain at ports. The lean supply chain focuses on eliminating waste in the supply chain. The model integrating six sigma and system dynamics to improve the lean supply at ports can be seen in Figure 10 below:

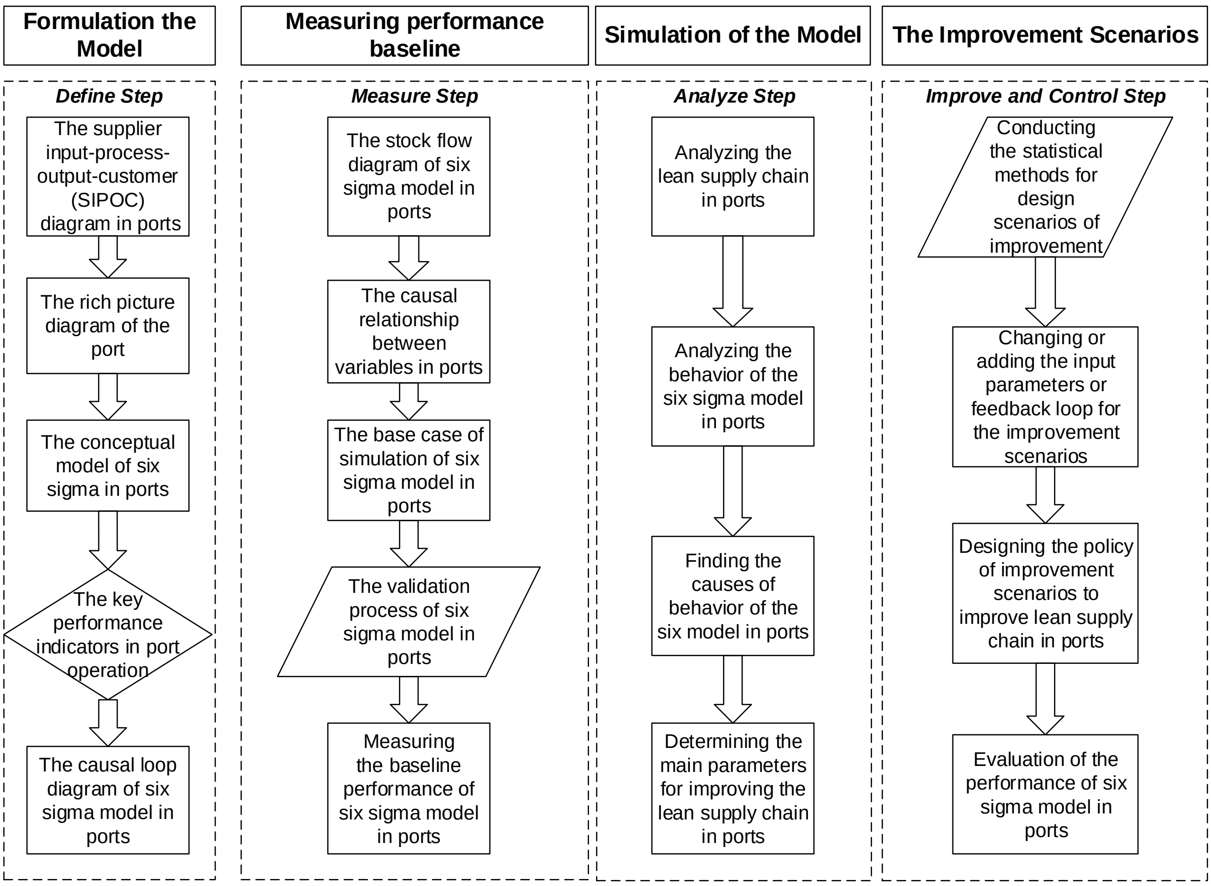


Figure 10.Integration model of six sigma and system dynamics for improving lean supply chain at ports

The integration of six sigma and system dynamics for improving the lean supply chain in ports complies with the DMAIC (Define-Measure-Analyze-Improve-Control) steps:

1. **Define steps**

   This step contains the formulation of a six sigma model in ports with the causal loop diagram after mapping the supply chain flow and determining the key performance indicators. Mapping of the supply chain flow in ports utilizes the SIPOC (Supplier-Input-Process-Output-Control) diagram and the rich picture diagram.

2. **Measure steps**

   These involve measuring the performance baseline of the six sigma model in ports after developing the stock flow diagram, running the base case of the simulation, and the validation process. The performance metrics are the sigma value, the process capability indices, and the cost of poor quality.

3. **Analyze steps**

   This involves analyzing the simulation results, including the lean supply chain in ports and the behavior of the six sigma model in ports. Then, the causes of behavior of the six sigma model are found, and the main parameters are determined for improving the lean supply chain in portsl.

4. **Improve and control steps**

   These contain the policy of improvement scenarios such as changing or increasing the input parameters, and changing or adding the feedback loop structures. The policy of improvement scenarios is developed and the performance of the six sigma model is then re-evaluated with the sigma value, the process capability indices, and the cost of poor quality.

This integration is used to improve the lean supply chain at ports because the system of the port is complex and the interaction between variables are dynamic. System dynamics approach enables to take into account dynamics of variables in ports as a complex system. Performance metrics are used to monitor the performance baseline and to know how well the improvements have been done with the increasing of the sigma value, the process capability indices, and the cost of poor quality. The sigma value is to measure the process variability in the supply chain through cargo-handling processes such as damages or defects, loss, equipment breakdown, transporter breakdown, the equipment and transporter delay time, etc. The process capability indices are used to measure the capability of the process in fulfillment of customer specifications. The cost of poor quality is used to measure the service quality of the port and focuses on the poor quality cost factors of ports.

3.2 Research Methodology Framework

This research follows the framework of the research methodology depicted in the flow chart in Figure 11 below:

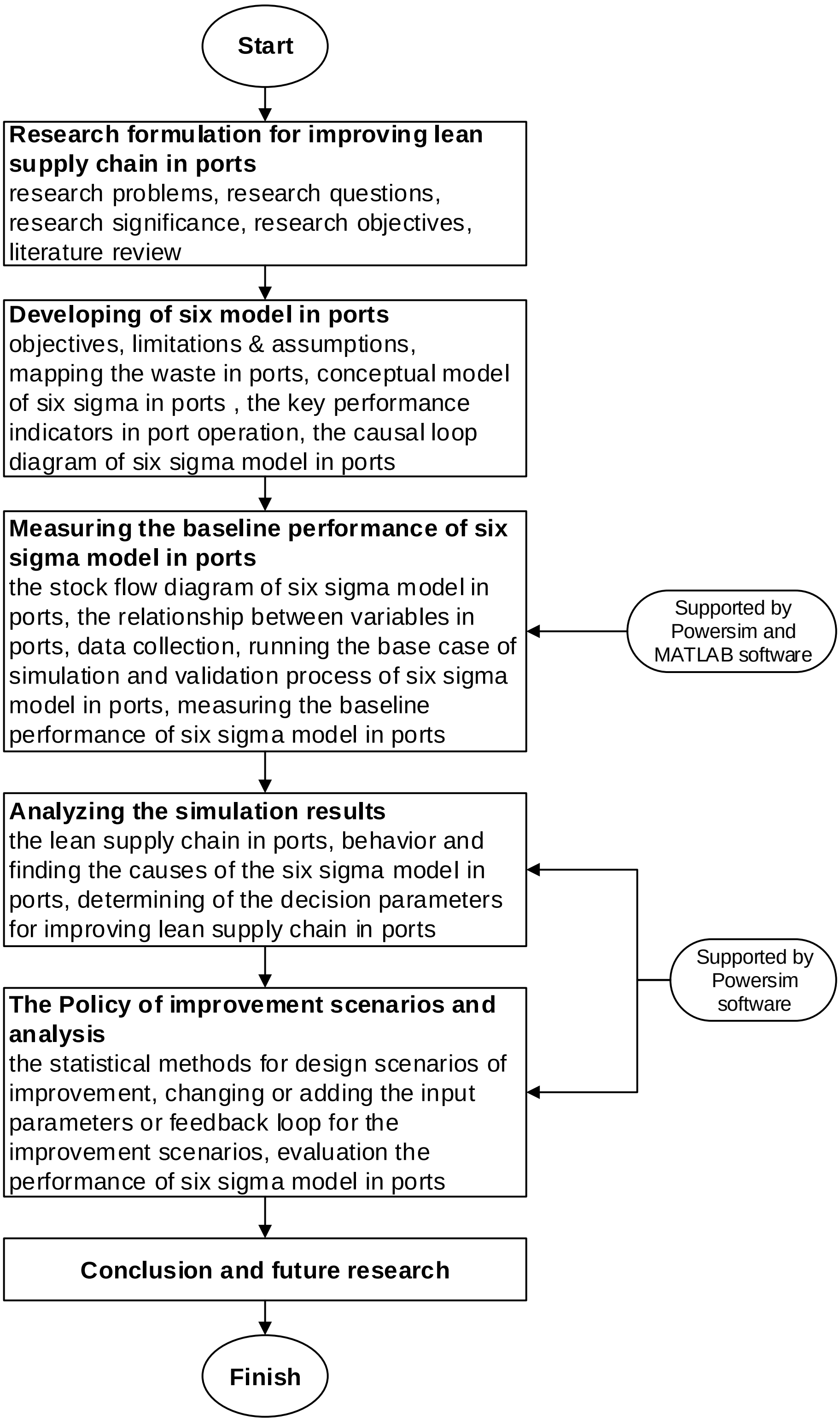


Figure 11.Flow chart of research methodology framework

The framework describes the main steps of this research, as explained below:

1. **Research formulation**

The research formulation is the conceptual step to developing an overall model that will cover the overall research objectives. This step contains research problems, research questions, research objectives, boundaries, and assumptions. A literature review of relevant journals is needed to know about recent research and determine the state of the art. The research formulation can be seen in Figure 12 below:

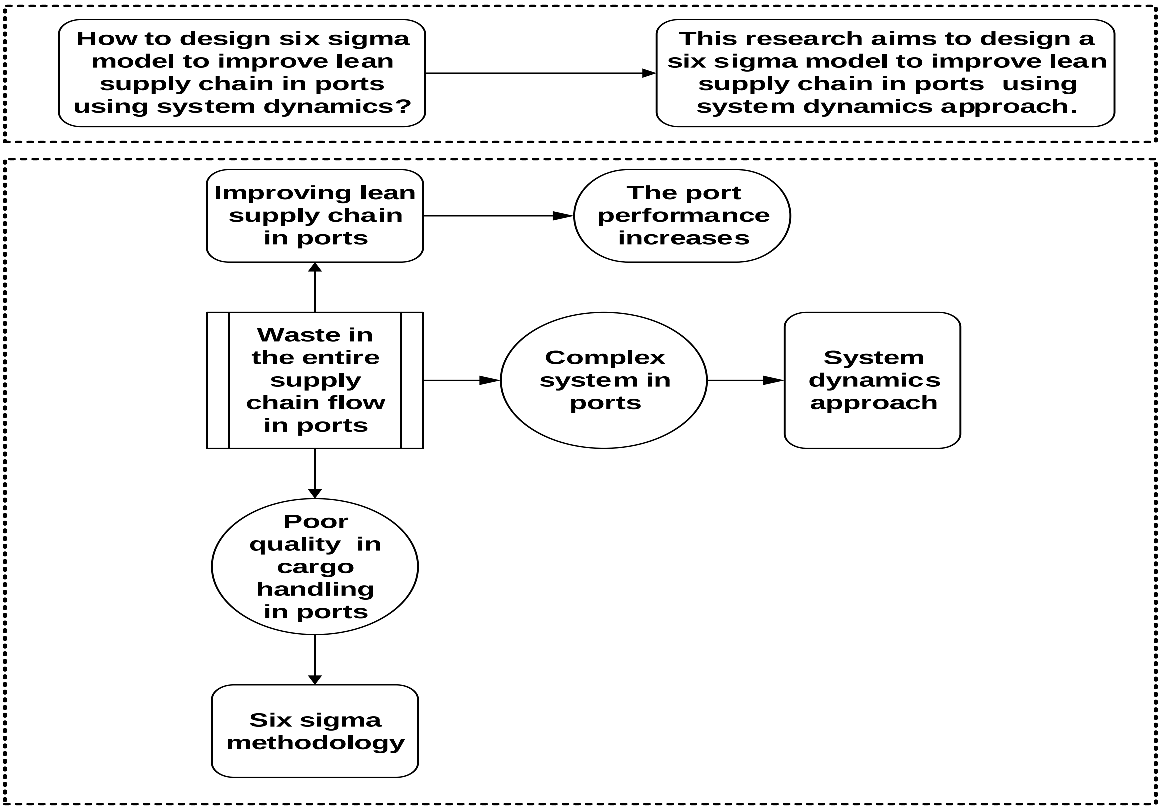


Figure 12.Research formulation

From Figure 12, the problems at ports, as complex systems, require a tool that can eliminate waste and reduce the poor quality so that the port becomes more effective and efficient. This research uses system dynamics to improve the lean supply chain at a port, integrated with six sigma methodology. How should this be modeled? This research aims to design a six sigma model of the lean supply chain at a port and then to improve the model with a simulation using the system dynamics approach.

2. **Development of model**

The model development starts by determining the objectives, boundaries, and assumptions. Mapping of the supply chain flow at the port is done using the SIPOC (Supplier-Input-Process-Output-Customer) diagram. The key performance indicators in ports as output variables are determined based on discussion with experts, the literature review, and direct observation at the port. Also, the parameters of the input variables in the port are determined. A causal loop diagram (CLD) is developed to describe the causal relationship between variables. The CLD is divided into three general models: the port operation, the port quality level, and the port performance metrics.

3. **Measuring the performance baseline of the model**

   The stock flow diagram (SFD) is developed with Powersim software and is developed by the three general models: the port operation, the port quality level, and the port performance metrics. The relationships between variables are determined and supported by MATLAB software. Data collection in the real case is required to run the base case of the simulation. Certain parameters are determined to execute the simulation. The validation process is performed with the actual data in port. According to Sterman (2000), the validation process of the dynamic models was performed with a boundary test, assessment of the structures, dimensional consistency, parameters assessment, extreme condition, integration error, and behavior reproduction.

4. **Analyzing the simulation results**

   The results of the simulation of the lean supply chain concepts and the behavior of the model are analyzed. The causes of deviation in the relationships between variables and the behavior of the output variables are found. Decision parameters are determined based on discussion with experts in ports and literature surveys.

5. **The policy of improvement scenarios and analysis**

   Scenarios are developed for improving the lean supply chain in the port. Changing or adding decision parameters is performed to get the optimal solution for the port. Also, changing or adding the feedback loops can be conducted to improve the lean supply chain in the port. The performance metrics evaluate the port’s performance. The sigma value, the process capability indices, and the cost of poor quality are re-evaluated to assess the performance improvements. The policy of improvement scenarios is determined based on the key performance indicators needed to improve the performance of the port, and is then analyzed to find the best solution.

6. **Conclusion and future research**

   The conclusion provides closing statements. Future research is recommended to continue this research.

Chapter 4

Model of the Causal Loop Diagram

4.1 Objectives

This model aims to improve the performance of ports. The model focuses on the sources of waste in ports, such as the vessel waiting time, delay time of equipment and transporter, equipment and transporter breakdown, and lost and damaged cargo. All these sources of waste in ports cause the internal failure cost. The model consists of three submodels, namely the port operation, the port quality level, and the port performance metrics. The port operation consists of the discharging rate, berth occupancy ratio, vessel waiting time, and cargo throughput; the port quality level consists of conformance costs, non-conformance costs and opportunity costs, where the conformance cost involves prevention and appraisal costs and the non-conformance cost involves internal and external failure costs. The Port performance metrics consist of the sigma value and process capability indices.

Firstly, the relationships between variables were developed in the sub-model. Then, a causal loop was constructed between variables and polarity was assigned to each variable, reinforcing or balancing. Secondly, the polarity was developed and a causal loop was identified between variables. This research is designed to determine improvement scenarios to reduce the vessel waiting time and the internal failure cost. The vessel waiting time influences the number of unloaded vessels that can be discharged from the port so that the cargo throughput will increase in a given period. The berth occupancy ratio is utilized as a parameter that influences the vessel waiting time. The internal failure cost influences the cost of poor quality, which will decrease the port performance. The conformance cost, which involves prevention and appraisal costs, is utilized as a parameter that influences internal failure costs such as demurrage cost, repair cost, lost cargo cost, and damaged cargo cost. The sigma value and process capability indices are metrics to measure the poor quality of the sources of waste such as delay time of equipment and transporter, equipment and transporter breakdown, and lost and damaged cargo.

4.2 Limitations and Assumptions

The six sigma model of the port using a system dynamics simulation is a general model. It requires certain assumptions and limitations for implementation in the real world. Some of these limitations and assumptions are explained below:

a. It can be applied in ports, specifically in dry bulk ports
b. Cargo-handling process focuses on unloading of vessels in the unloading or import terminal.

c. Performance metrics in the port utilize six sigma tools, namely the sigma value and process capability indices (Cpk).
d. The six sigma model in the port focuses on measurement of the cost of poor quality, which is related to lean activity such as equipment or transporter delay, equipment or transporter breakdown, lost or damaged cargo, and demurrage cargo.
e. Uncontrollable variable factors are ignored, e.g : bad weather, natural disaster, unexpected equipment and transporter breakdown, etc.
f. The waterways system and users are beyond the scope of this research because the complexity of including these issues would go beyond the scope of this thesis.

4.3 The Process Mapping of the Supply Chain

The first step in mapping the supply chain process is the SIPOC (Supplier-Input-Process-Output-Customer) diagram. Barone and Franco (2012) mention that the SIPOC diagram can assist in the stage of identification process of an organization. This diagram is applied to identify each stream of the supply chain. The five streams in this diagram are supplier, input, process, output, and customer. The second step in mapping the supply chain is making the rich picture diagram, which is utilized to represent the process of the supply chain flow as an attractive picture. The SIPOC diagram gives an understanding of the process flow in a simple form with the relationships among its components. For the analyzed SIPOC diagram, firstly, it is suppliers who provide inputs and these can be stakeholders. Second is input that represents what the suppliers want and this is the essential requirement for the process flow of work. Third is the process, which is the procedure for transforming the input to become the output. Fourth is the output, which is the result of transforming the input. Last is the customer, who is the recipient of the output process. These are not only buyers but also users of the output at every step in the transformed process. The SIPOC diagram can be viewed in Table 2 below:

Table 2.SIPOC diagram in ports (modification from Jafari (2013b))

Supplier	**I**nput	**P**rocess	**O**utput	**C**ustomer
- Loading/Unloading Companies - Shipping lines - Owner of ships - Owner of goods - Transportation Companies	- Materials - Resources - Equipment and manpower - Goods, container, truck and train	Refer to Figure 13	- Delivery of goods and container from/to ship - Delivering goods to owners	-Owner/ Distributor of goods - Individual

The process steps in ports consist first of the vessel arriving to be moored in port as shown in Figure 13. The next process is the loading and unloading process from the vessel to the intermodal connectivity that delivers the goods and containers to the designated spaces.

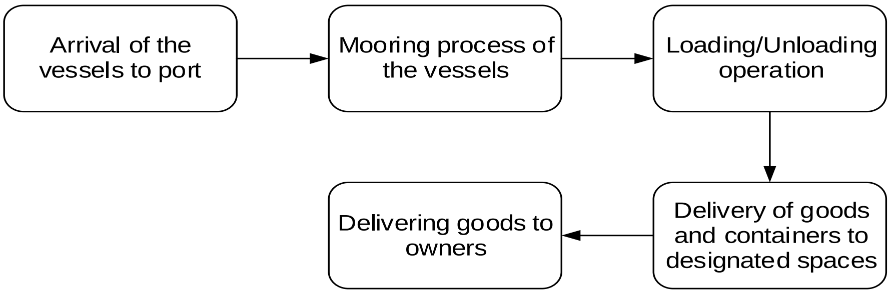


Figure 13.Process flow in ports based on the SIPOC diagram

The rich picture diagram can help to explore, acknowledge and define the situation and express it attractively through a diagram. Bronte and Stewart (1999) mention that the benefit of the rich picture diagram is as a technique to represent particular aspects in a situation, and as a vehicle for communication among stakeholders. The rich picture diagram can be used as a learning process on how this diagram representation is interpreted so that we can appreciate the potential strength of these diagrams. The rich picture diagram of the port area generally can be depicted as in Figure 14:

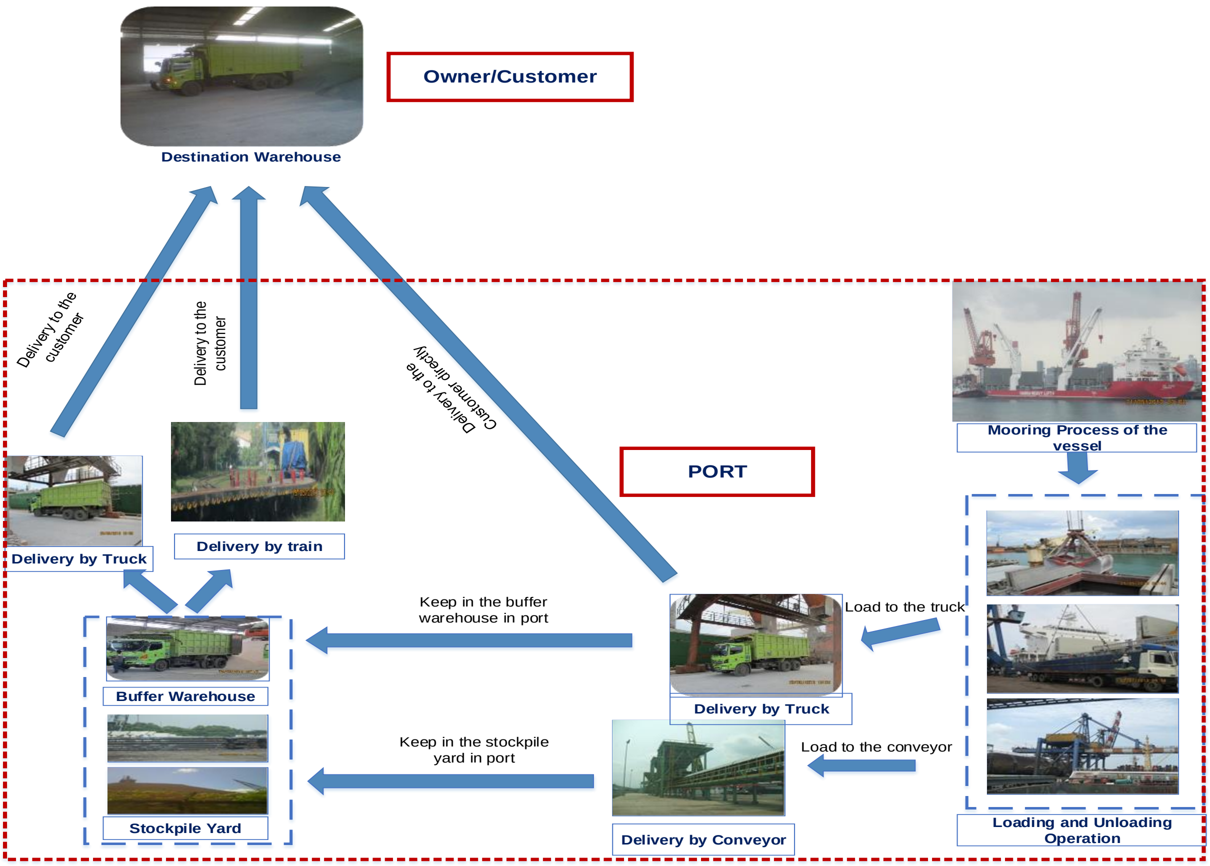


Figure 14. Rich picture diagram of the port

4.4 Conceptual Model of Six Sigma Model in The Port Using System Dynamics

This model uses three parts, the port operation, the port quality level, and the port performance metrics. The port operation consists of three parts, namely the sea side, the land side, and the performance indicators of port operations. The port quality level focuses on the cost of poor quality (COPQ), which consists of the conformance cost, non-conformance cost, and opportunity cost. The port performance metrics focus on the performance metrics of the six sigma methodology, namely the sigma value and process capability indices (Cpk). The conceptual model can be drawn as in Figure 15 below:

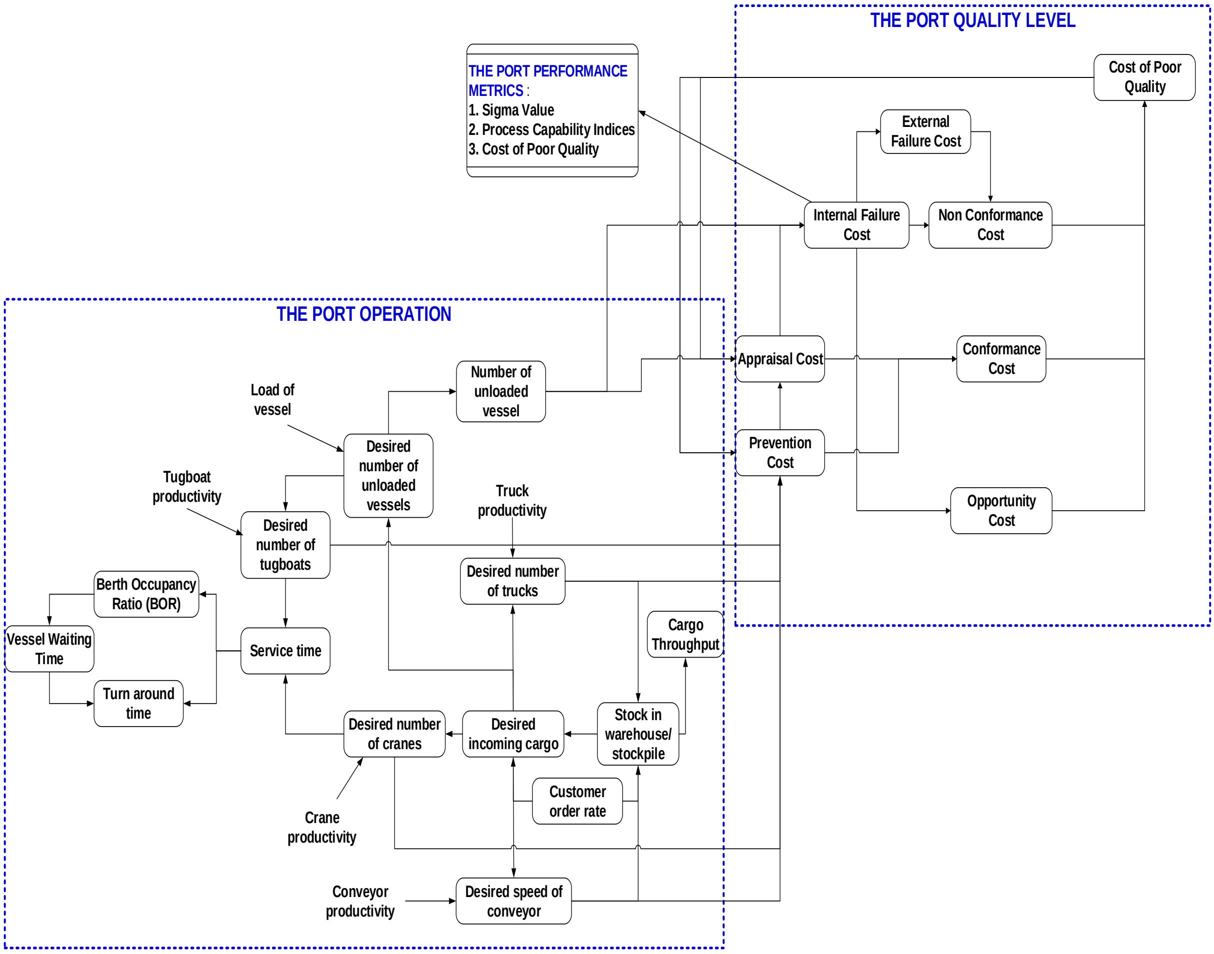


Figure 15.Conceptual model of six sigma in ports using system dynamics

Based on Figure 15, the port quality level contains the service activities in ports that affect the cost of poor quality (COPQ), namely the conformance cost, non-conformance cost, and opportunity cost. These activities focus on the equipment and transporters that are utilized in the port operation. The utilization of cranes in the port operation influences the service time of loading and unloading in the cargo handling, while trucks, conveyors, and tugboats are the transporters used in the port operation. All of these need preventive maintenance activities, which can influence the prevention cost. Unloaded vessels in berths require appraisal or inspection activities that relate to the appraisal cost, such as the draft survey cost, customs clearance cost, and cargo inspection cost. The prevention and appraisal activities influence the internal failures in the port, such as lost cargo, damaged cargo, demurrage, and equipment and transporter damage or repair. All of the internal failures cause costs that have to be taken into account.

This model focuses on the prevention and appraisal activities that can cause internal failures in ports. The port performance metrics are utilized to measure the internal failures with a sigma value and process capability indices. The sigma value is used to control the process variability in ports and the process capability indices (Cpk) are needed to know the process capability in fulfillment of customer specifications. The port operation focuses on the material flow in the port. The berth occupancy ratio (BOR) and the vessel waiting time, and the cargo throughput are factors in the port operation performance. The productivity of cranes and tugboats influences the service time in ports. The service time can reduce the BOR and vessel waiting time so that the cargo throughput can increase in a particular period. This research focuses on reducing the vessel waiting time with the BOR value as an indicator. The relationship between the BOR and the delay factor or the vessel waiting time follows the exponential distribution based on Monie (1987). From this graph, the vessel waiting time will increase sharply after the BOR value reaches more than 80 %. Therefore, reducing the vessel waiting time is a trade-off due to the BOR value as an indicator of the berth utilization that influences to the cargo throughput. Also, the vessel waiting time influences the cargo throughput. The value of BOR that is considered here is safe, i.e. in range of 60 - 70 % (UNCTAD, 1982). According to Alderton (2008), the BOR value is around 70 % for the general-purpose berths. If the BOR value is too large, the port is encountering the serious possibility of congestion. On contrary, if the BOR value is too small, the management of port could indicate over investment.

This model can be implemented in ports. Based on Feasibility Analysis of System Dynamics for Inland Maritime Logistics (2014), the research area in ports includes five areas: vessel, ports, intermodal connectivity, waterways, and users. Based on Figure 16 below, this research focuses on three areas: vessels, ports, and intermodal connectivity. The material flow starts from the mooring process of the vessels with a tugboat. The number of tugboats depends on the vessel arrivals. After the vessels arrive in the berths, the unloading process is conducted using cranes. This area involves the sea side and the land side in the ports. Then, the cargo is transferred to the warehouse or stockpile yard using intermodal connectivity such as trucks and conveyors.

The research area of this thesis is depicted in Figure 16 below:

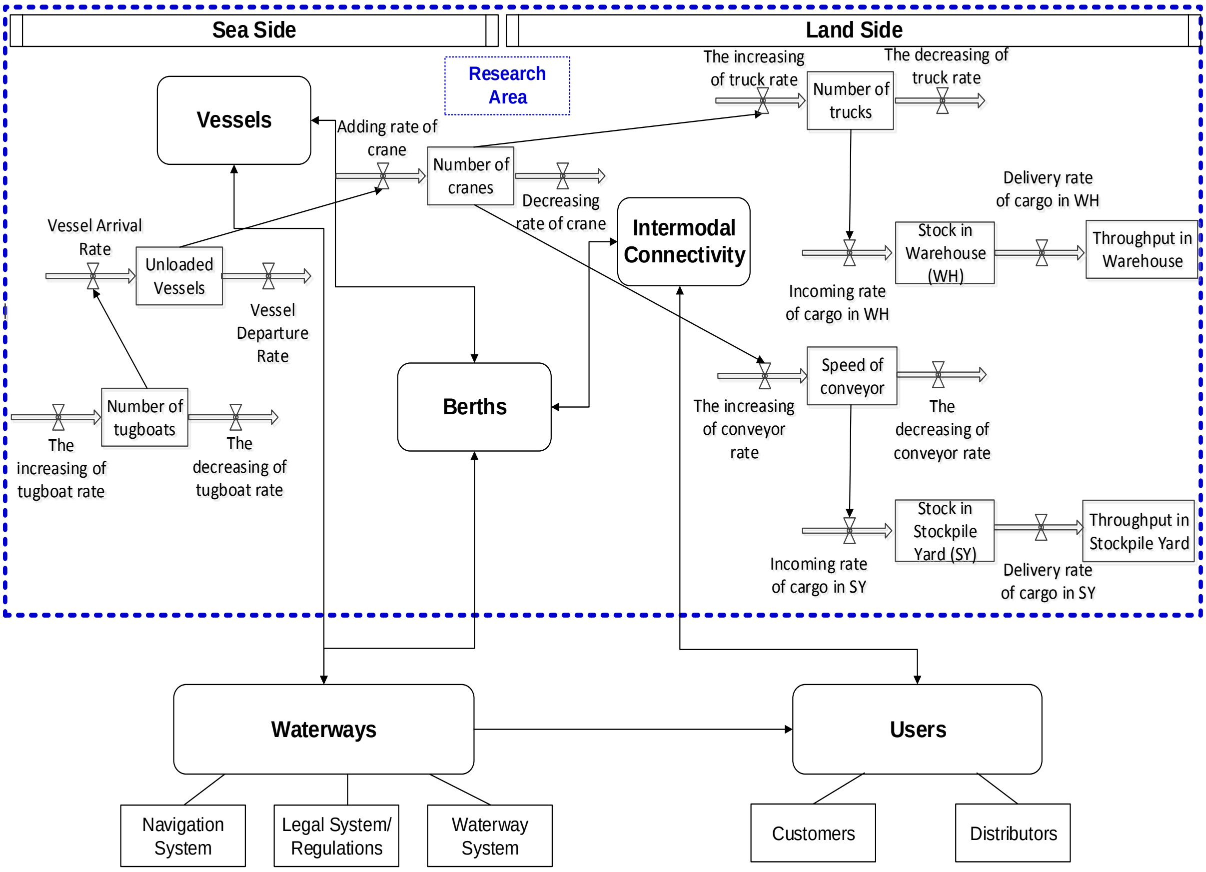


Figure 16.Research area of the material flow in ports (developed from the model of the Maritime Freight Transportation System by Schneider et al. (2014))

The port operation sub-system contains the material flow in ports. Woo et al. (2012) mention that the terminal operation of a port consists of the sea operations, the yard operations, and the land-side operations. First, the sea-side operations focus on the process planning of the vessel, such as berth allocation, scheduling of the quay crane, planning of storage, and queuing problems. Second, the yard operations deal with the design of the storage space, the cranes at the yard, and the carrier transport. Last, the land-side operations are concerned with the truck and rail operations and optimization of the modal split. In this research the port operation consists of the sea-side and the land-side based on the model of the Maritime Freight Transportation System (Schneider et al., 2014).

The sea side involves the vessel activities for mooring in the berth. Fully loaded vessels will be brought to the berth by tugboats and moored to available berths in the port terminal. The time taken for this process depends on the tugboat productivity and is known as the approach time. The land side involves the berthing activity using cranes. After the vessels have berthed securely, the cranes available at the berths start to unload the cargo. The time required for discharge of the cargo depends on the productivity of the cranes. The time required to unload the cargo of the vessels, from berthing until the vessels are unberthed is the berthing time. The service time in the port involves the approach time and berthing time.

The vessels' cargo can be unloaded by grabs and then loaded directly into trucks or onto a conveyor belt.

The land side focuses on the vessels' cargo, which is delivered by intermodal connectivity directly to the buffer warehouse in the port or the destination warehouse. Also, several cargos are delivered by intermodal connectivity directly to the buffer stockpile or the destination stockpile. The performance indicators of port operations are the berth occupancy ratio (BOR), the vessel waiting time, and the cargo throughput.

The endogenous variables of the port operation are the desired number of tugboats, the expectation of vessel arrival, vessel unloading, the desired number of cranes, the desired number of trucks, the desired speed of the conveyor, the stock in the warehouse/stockpile, and the cargo throughput. The exogenous variables are the customer order rate, tugboat productivity, crane productivity, truck productivity, and conveyor productivity.

The port quality level sub-system involves the service quality of the port and focuses on the quality cost factors of ports, especially the quality cost of poor quality (COPQ). Many activities in ports involve connected variables and cause the costs. The COPQ consists of the conformance cost, non-conformance cost and opportunity cost. The conformance cost involves control activities to prevent or detect poor quality. The conformance costs in ports consist of prevention and appraisal costs that aim to prevent and assess poor quality in the cargo-handling process. Secondly, the non-conformance cost involves the failure activities to react to poor quality. The non-conformance costs consist of demurrage costs, lost cargo costs, damaged cargo costs, and repair costs. Lastly, the opportunity cost involves activities that are estimated as a profit, but are not taken into account. The opportunity costs in ports consist of compensation costs for a worker on training, compensation costs for lost and damaged cargo, and compensation costs for equipment and transporter repair or maintenance. This interpretation of the opportunity cost in ports is based on literatures and discussion with the expert of port.

The port performance metrics sub-system contains the sigma value and process capability indices. The sigma values and process capability indices are measured in the sources of waste in the cargo-handling process in ports. The sigma value and process capability indices focus on lost cargo, damaged cargo, equipment and transporter breakdown, and delay time of equipment and transporter. Calculation of the sigma value and process capability indices is based on continuous or discrete data. This research only uses an aggregate perspective for the sigma value and process capability indices approach instead of looking at myopic sigma value and process capability indices reference objects and their interactions. The sigma value and process capability indices (PCI) are the parameters of the port performance. According to Ridwan and Noche (2014b), calculation of the sigma value of the cargo handling process in the port shows the performance baseline to be improved. Also, according to Ridwan and Noche (2014a), the PCIs were applied in the supply chain flow of the cargo handling in a port, and indicated that the process capability in cargo handling was capable of meeting the customer requirements. Some improvements could be proposed for increasing the PCIs. Alnahhal et al. (2014) investigated the waste at workstations and if the material was delivered just in time, another waste, namely excess inventory, was decreased.

4.5 The Key Performance Indicators

The key performance indicators are required to determine the variables that significantly influence the performance. This research focuses on the three key performance indicators in port operation, i.e. the berth occupancy ratio (BOR), the vessel waiting time, and the cargo throughput. The vessel waiting time relates to the operation time that is one of the service indicators. Meanwhile, berth occupancy ratio is one of the utilization indicators. Therefore, reducing the vessel waiting time obviously is part of a trade-off due to the BOR value as an indicator of the berth utilization. Also, the vessel waiting time influences the cargo throughput. Firstly, according to Alderton (2008), the BOR is the ratio between the time of a berth being occupied and then becoming available again in a particular period. The BOR is influenced by the vessel service time, the number of unloaded vessels, the number of available berths, and the available time in the port operation The BOR value is depending on the service time, the number of unloaded vessels, the number of available berths, and the available time in the port operation. The arrival of unloaded vessel and service time have variability in their processing. Basically, the arrival rate is distributed randomly such as poisson distribution. Our research uses pull system approach so the arrival of unloaded vessel follows the customer order rate of the cargo in the ports. The service time is depending on the approach time and berthing time. The service time in the port includes the approach time and berthing time. The approach time is the time required to bring a vessel for the mooring process (piloting service) in berths. The berthing time is the time required to unload the cargo of the vessel, from berthing until the vessels are unberthed.The approach time is depending on the productivity of tugboat and the number of tugboats. The tugboat productivity is influenced by the capacity of tugboats and the number of tugboats. The berthing time is depending on the load of the vessel, productivity of crane and number of cranes. The crane productivity is influenced by the crane lifting capacity and crane operation cycle. Thoresen (2014) explained that the BOR is a necessary requirement to determine the number of berths. The second key performance indicator of port operation is the vessel waiting time. De Monie (1987) presents a correlation between the BOR and the vessel waiting time. The vessel waiting time is influenced by the BOR value. Erlang’s ideas in Alderton (2008) indicate that the vessel waiting ratio increases quite dramatically if the number of berths decreases.

The last key performance indicator, the cargo throughput, relates to how much cargo can be loaded or unloaded in a port in a particular period and is influenced by several factors: the type of cargo, the technology used, the route for the cargo, etc. The cargo throughput is also a performance indicator to monitor whether the utilization of equipment and transporters in a certain period is productive or not. In this research, the cargo throughput is not measured as an effect of the utilization of equipment and transporters because this research uses pull system approach. In pull system approach, this research focuses on the active number of equipment and transporters for the cargo handling process in ports. All equipment and transporters are made to reach as equilibrium condition. Therefore, increasing the cargo throughput obviously is part of a trade-off due to the availability of equipment and transporters as an indicator of the berth utilization. Meanwhile, four key performance indicators of the port quality level are failure cost, which consists of demurrage costs, repair costs, lost cargo costs and damaged cargo costs. Demurrage costs are influenced by equipment or transporter delay time because of repair or maintenance. The repair cost is affected by the equipment or transporter repair time. All data of equipment and transporters are taken from the historical data and not taken from the material flow directly. Meanwhile, the lost cargo and damaged cargo costs are influenced by prevention and appraisal activities such as cargo inspection activities, the budget for safety and security cost, etc.

4.6 Causal Loop Diagram

The causal loop diagram (CLD) is used to formulate a dynamics hypothesis in ports. The CLD involves the port operation, the port quality level, and the performance metrics sub-system. In building the model, the port quality level refers to the model developed by Kiani et al. (2009) as shown in Figure 17:

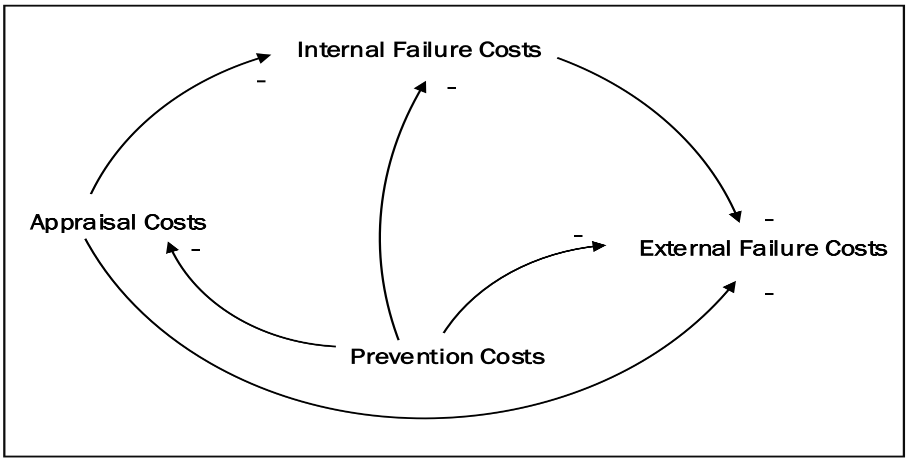


Figure 17. Causal loop diagram of cost factors (Kiani et al., 2006)

The port operation model refers to the model developed by Briano et al.(2009) and Sterman (2000) as shown in Figure 18 and 19:

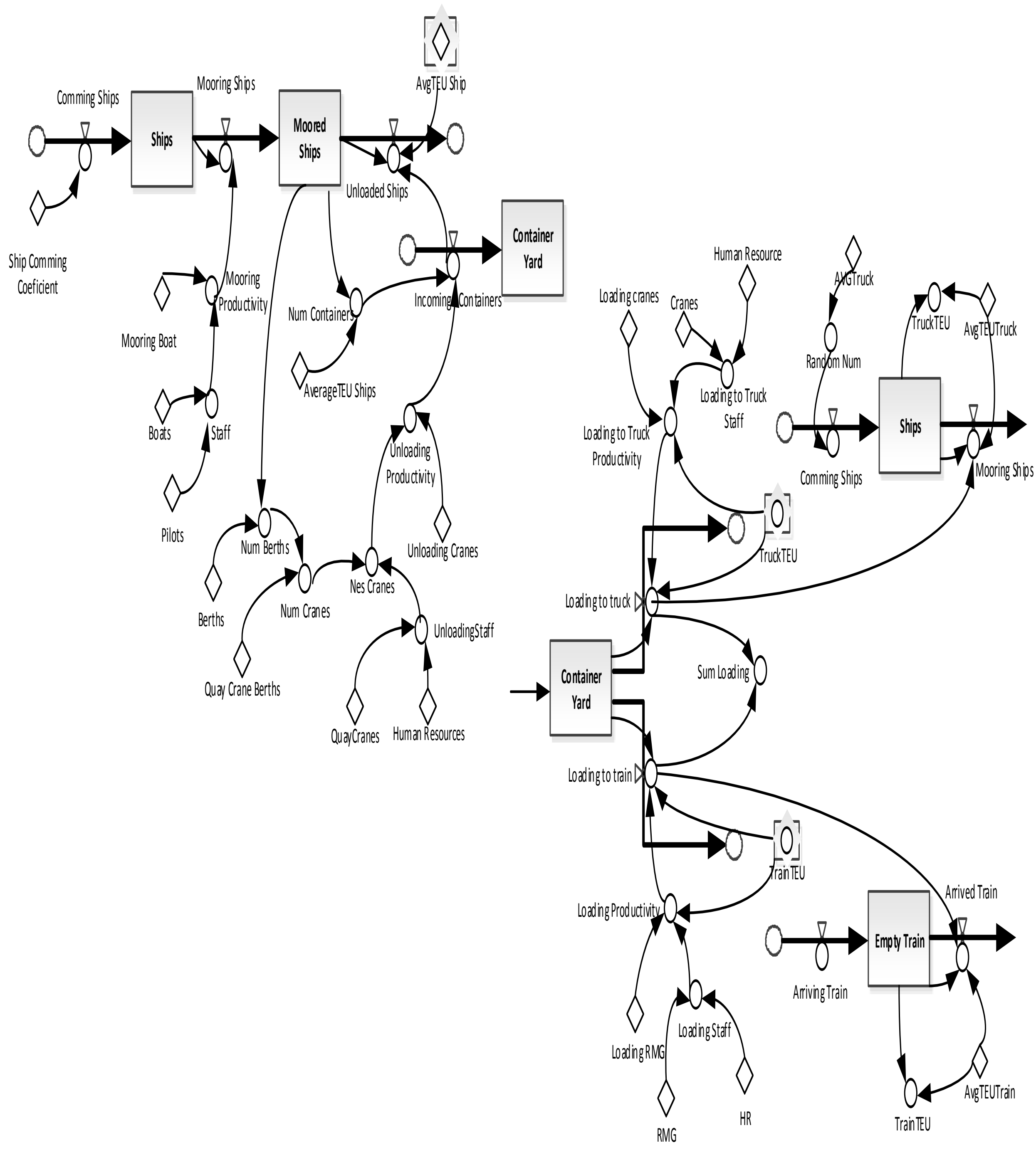


Figure 18. Simulation model of a container port terminal (Briano, et al., 2009)

From Figure 18, reference model of the port operation in a container port terminal and the feedback loop have not been completed. This model focused on the material flow.

The next reference model of port operation relates to the inventory management as shown in Figure 19:

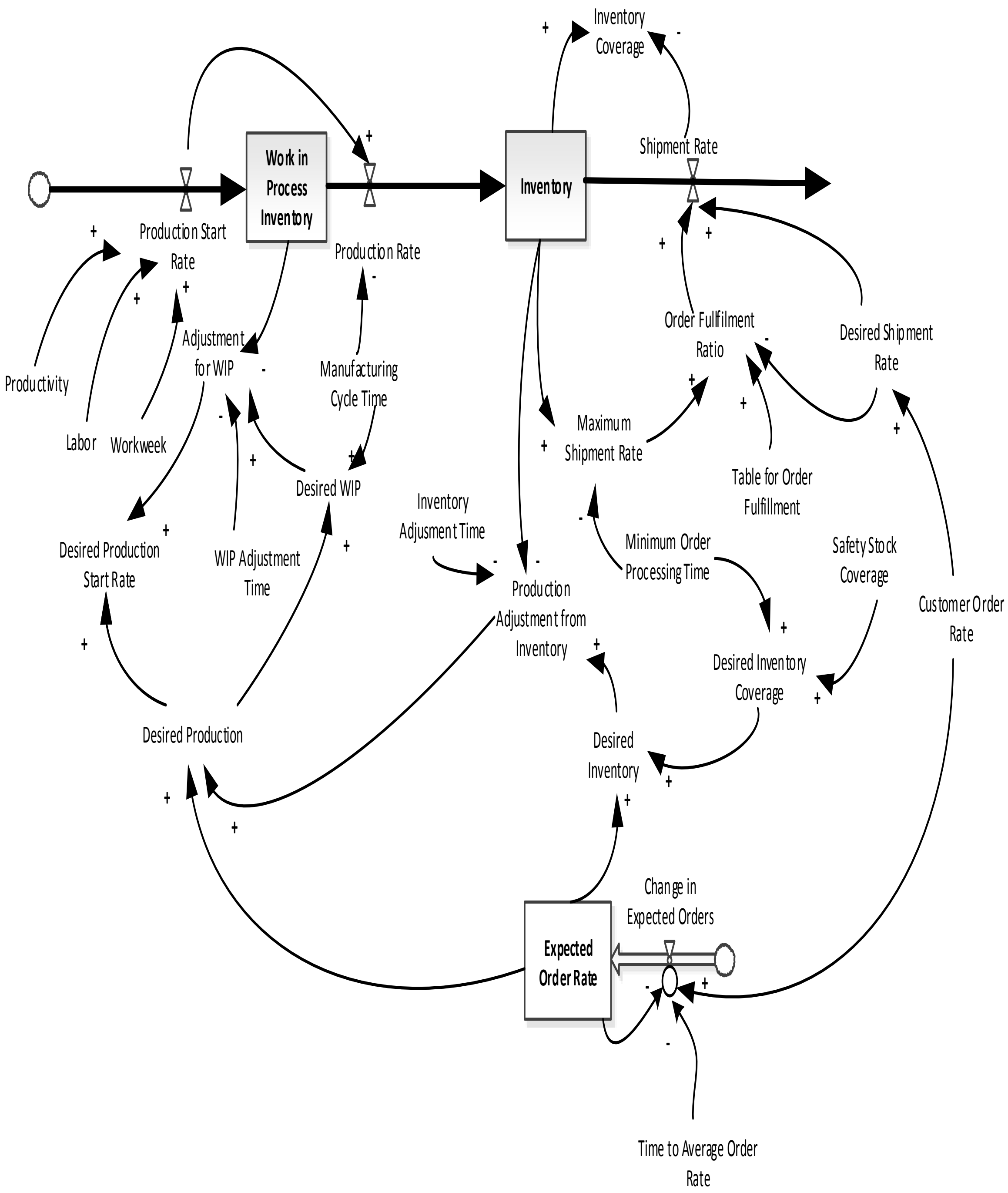


Figure 19. Inventory management (Sterman, 2000)

The complete general model can be seen in Appendix A. The CLD model of six sigma in the port is divided into three sub-systems as follows: 1) the port operation; 2) the port quality level; and 3) the port performance metrics.

The general model of six sigma in ports can be observed in Figure 20 below:

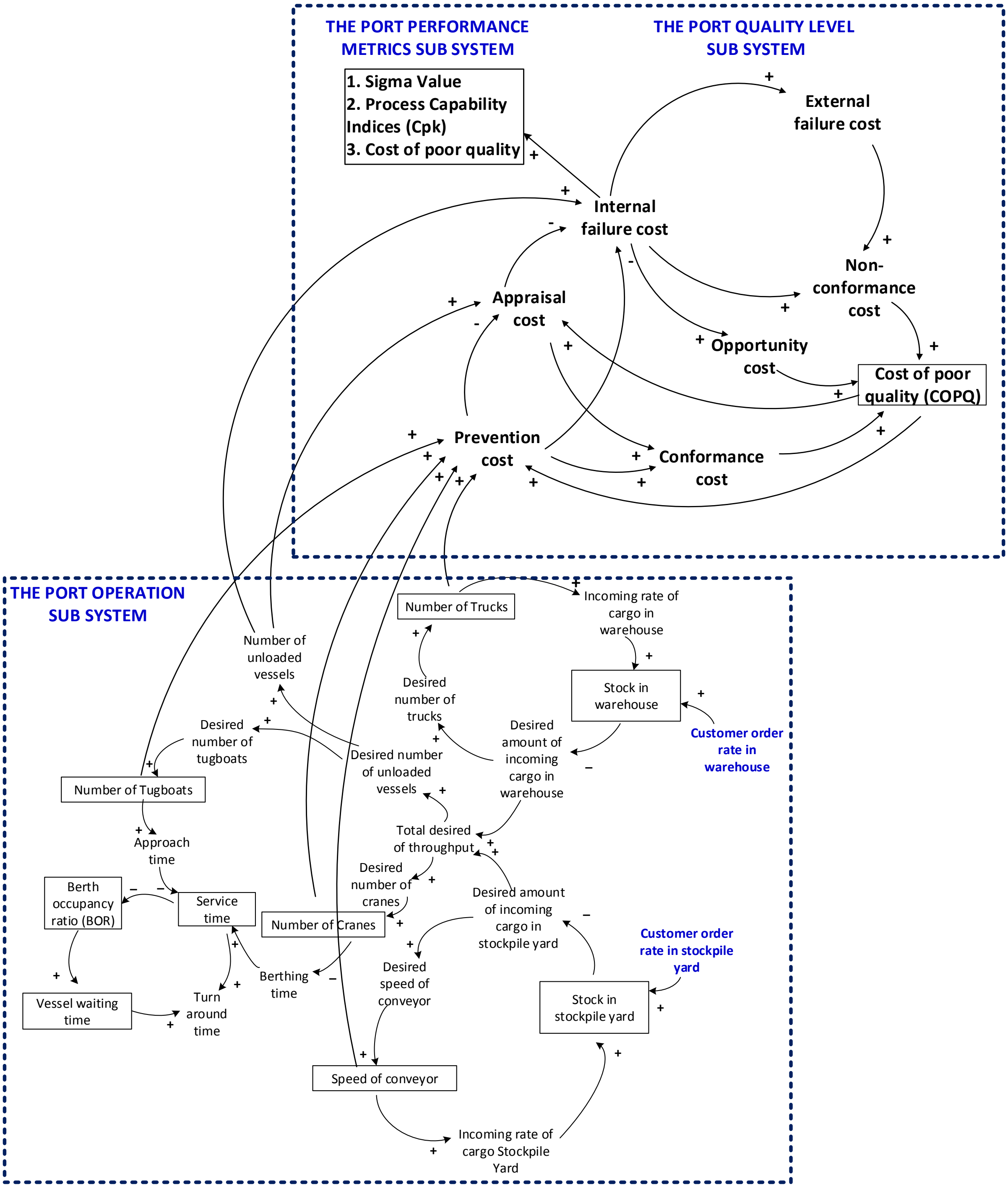


Figure 20.Causal loop diagram of six sigma model in ports

4.6.1 The Port Operation

The CLD of the port operation consists of the sea side, the land side, and the performance indicators of the port operation. The CLD can be seen in Figure 21 below:

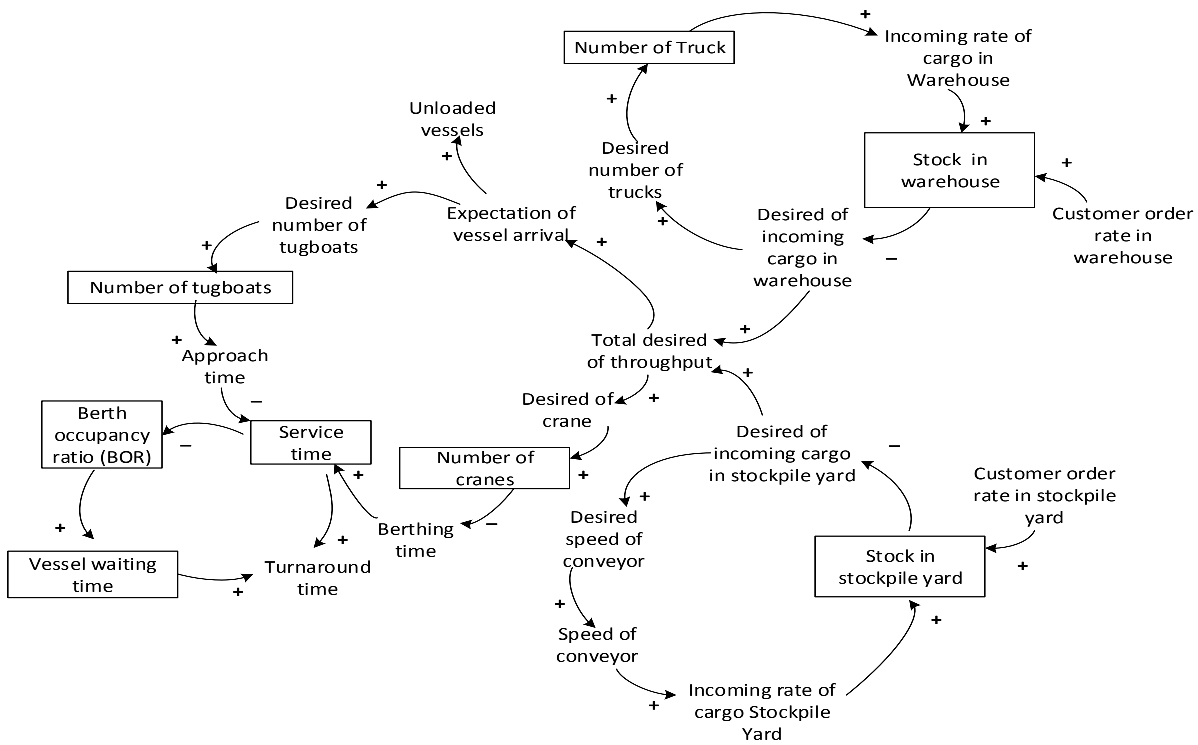


Figure 21. Causal loop diagram of the port operation

The CLD of the port operation can be seen in detail in Appendix A. The CLD of the port operation consists of the three main sub-systems:

1. **The sea-side sub-system**

   This CLD can give information about the numbers of vessels, the number of tugboats and number of cranes that are used in the sea side of the port operations. The exogenous variable for this sub-system is the total desired throughput in the port. There are three positive loops: changing the number of unloaded vessels, changing the number of tugboats, and changing the number of cranes, as shown in Figure 22 below:

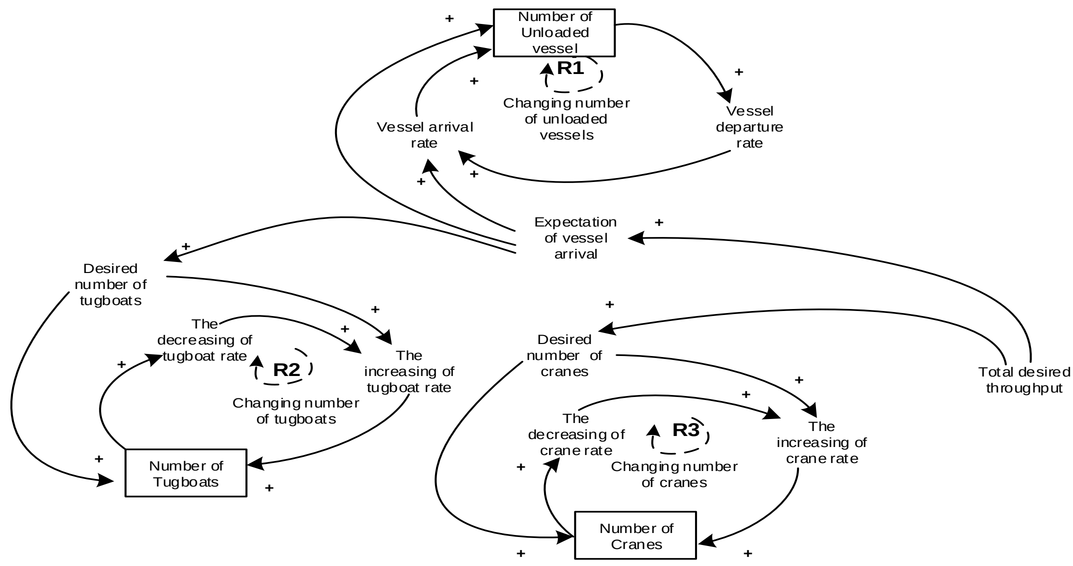


Figure 22. CLD of the sea side

2. **The land-side sub-system**

   This CLD gives information about the number of trucks, incoming goods in a warehouse, the speed of the conveyor, and incoming goods in a warehouse that are utilized on the land side of the port operations. The exogenous variable for this sub-system is the customer order rate in the warehouse and stockpile yard as shown in Figures 23 and 24. The complete CLD of the land side can be seen in detail in Appendix A.

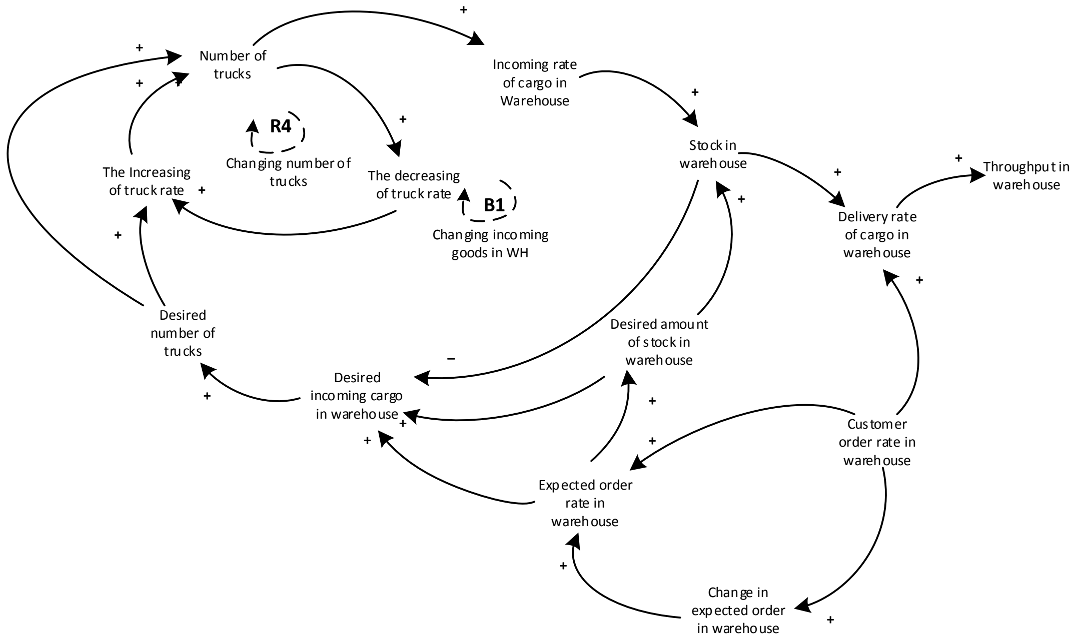


Figure 23. CLD of changing incoming goods in the warehouse

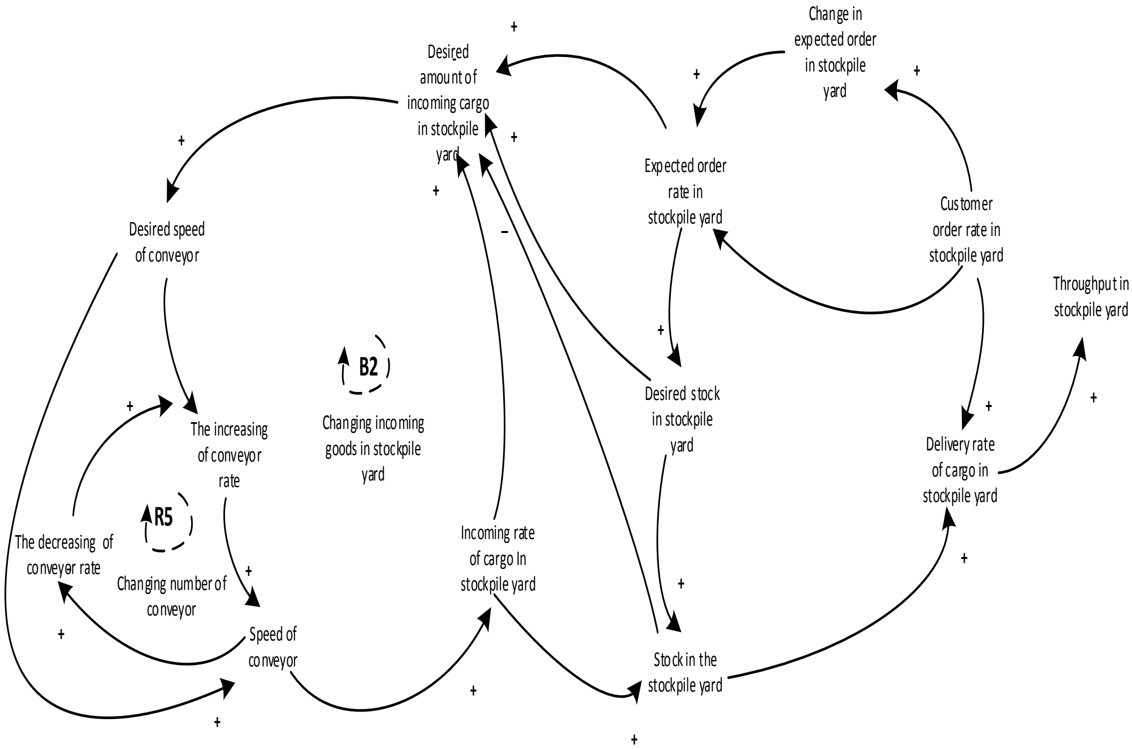


Figure 24. CLD of incoming goods in stockpile yard

3. The port operation performance

   This CLD gives information about the metrics of port operation performance. The exogenous variable for this sub-system is the number of tugboats, and the number of cranes, as shown in Figure 25 below:

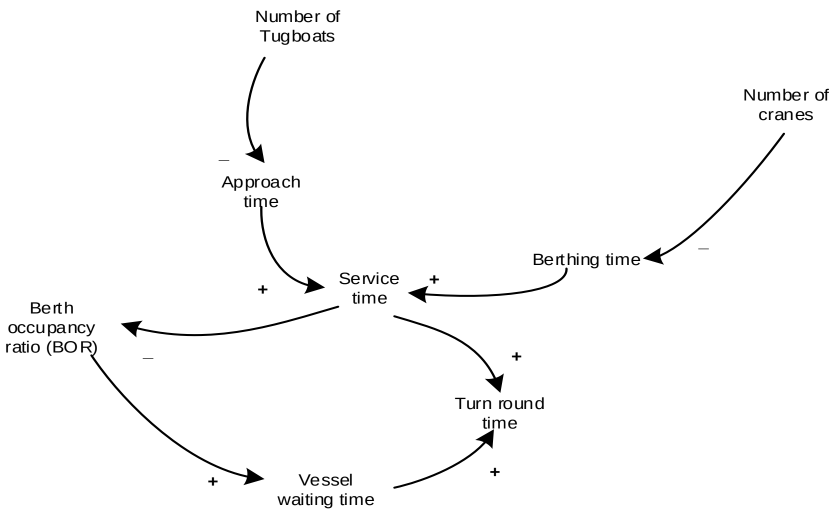


Figure 25. CLD of port performance

4.6.2 The Port Quality Level

The port quality level focuses on measuring the cost components of poor quality in ports. The CLD of the port quality level comprises the conformance cost, non-conformance cost, and the opportunity cost. The conformance cost involves the prevention cost and appraisal cost. In this research, the quality level focuses on measurement of the cost components. Prevention costs have reduced the internal failure of lost cargo and damaged cargo through the safety and security cost. Also, the prevention cost has reduced the internal failure of the transporter and equipment repair cost through the preventive maintenance cost. Besides influencing the internal failure costs, the prevention costs variables influence the appraisal cost. The transporter and equipment checking cost as a component of the appraisal cost is affected by the transporter and equipment preventive maintenance cost. Meanwhile, appraisal costs influence the decrease in internal and external failure costs. The appraisal cost can reduce the lost and damaged cargo cost and can also eliminate a percentage of undetected damage after shipping in the external failure cost component.

The external and internal failure costs positively influence the non-conformance costs. Likewise, the preventive and appraisal costs positively influence the conformance costs. Both the conformance and non-conformance cost have a positive link to the opportunity costs. Furthermore, the cost of poor quality (COPQ) is assigned to these three main cost components, all of which can cause an increase in the total COPQ. Ultimately, the quality level of the port is affected by the non-conformance costs. The CLD of the port quality level is depicted in Figure 26 below:

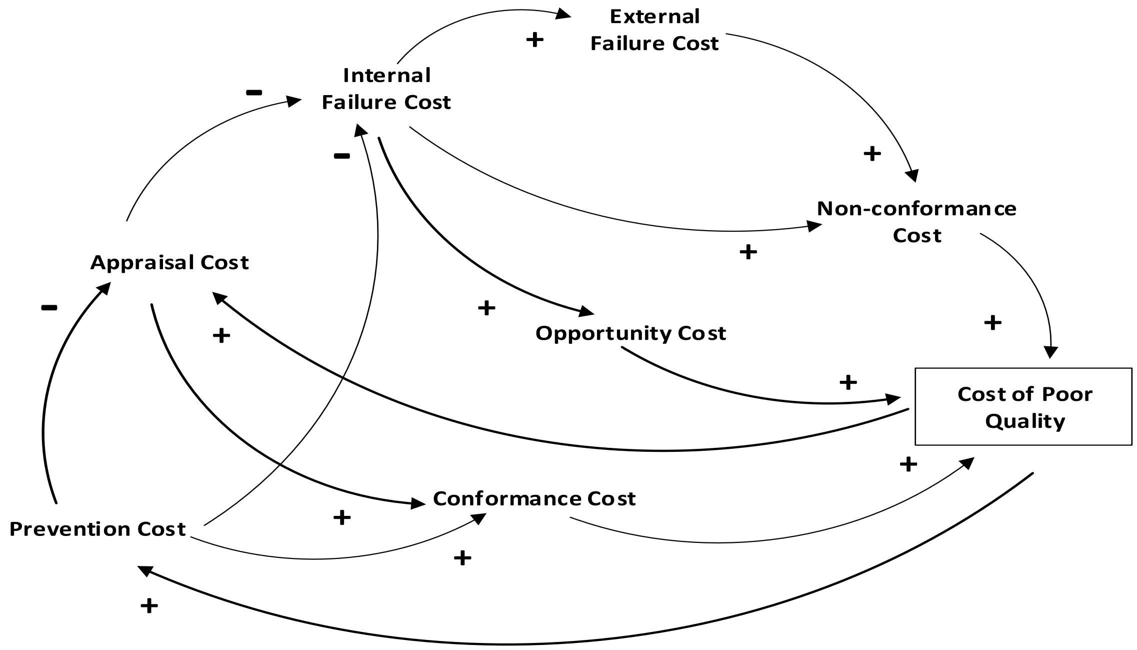


Figure 26. CLD of the port quality level

Next, the CLD of the non-conformance cost is affected by the internal failure cost and the external failure cost. The demurrage cost positively influences the internal failure cost components, namely the repair cost, damaged cargo cost, and lost cargo cost, whereas discounts due to the damage cost and complaint adjustment cost have a positive link to the external failure cost. The non-conformance cost can be seen in detail in Appendix A. The general CLD of the non-conformance cost is described in Figure 27 below:

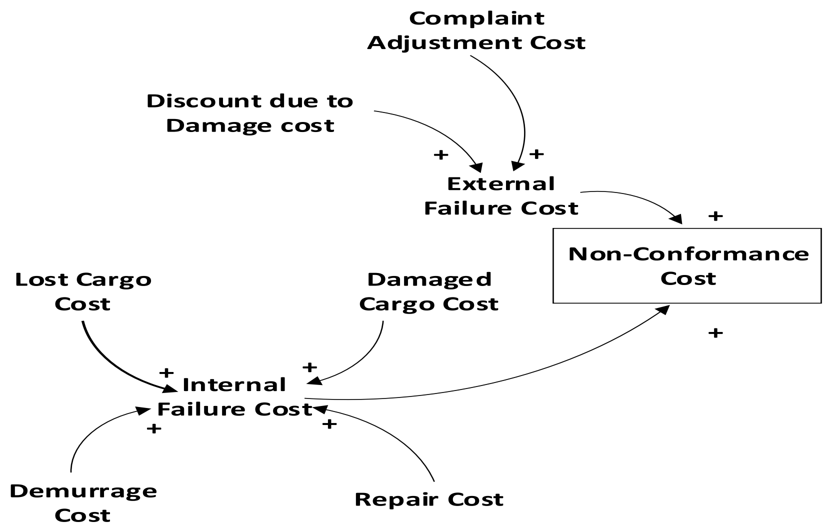


Figure 27. CLD of non-conformance cost

The CLD of the conformance cost consists of the prevention cost and appraisal cost with the components shown in Figure 28 below. The conformance cost can be checked in detail in Appendix A.

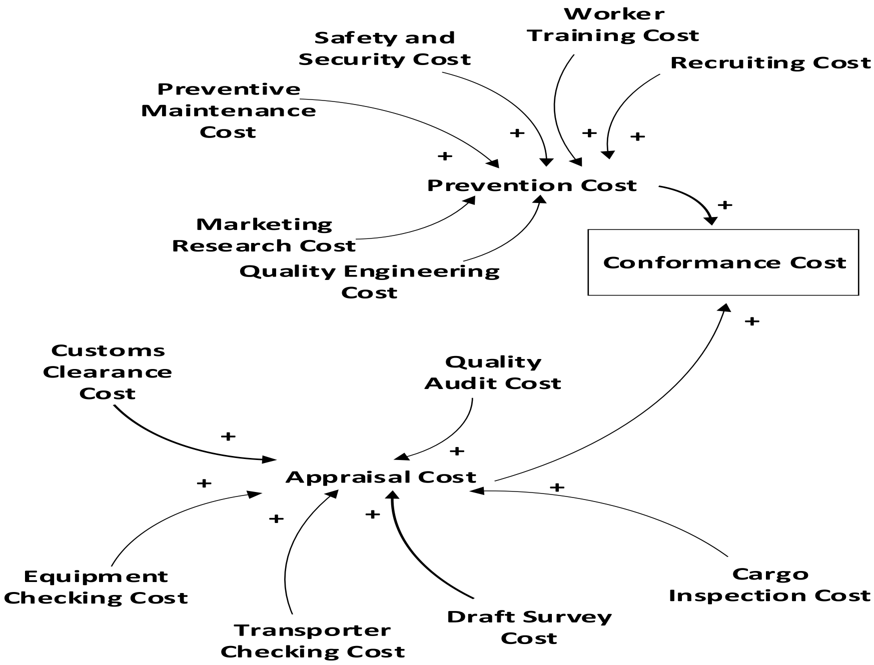


Figure 28. CLD of conformance cost

Finally, the cost components of the COPQ are the opportunity cost, which consists of the compensation cost for lost and damaged cargo; workers on training; and maintenance and repair of transporters and equipment. The CLD of the opportunity cost can be seen in Figure 29. The CLD of the opportunity cost can be observed in detail in Appendix A.

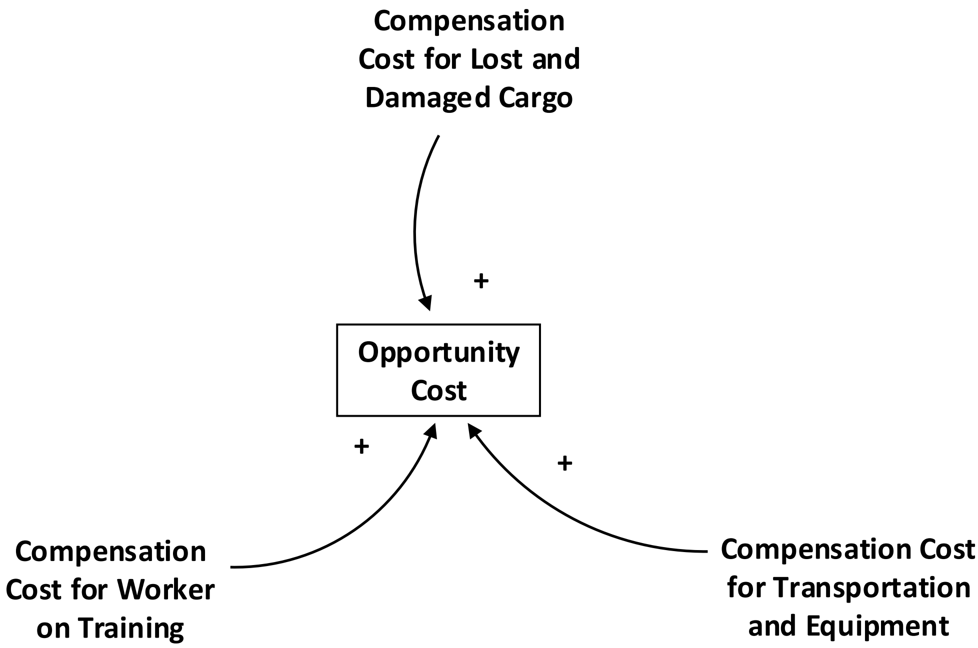


Figure 29. CLD of opportunity cost

The port quality level sub-system consists of several feedback loops, all of which are based on the discrepancies between the actual and target COPQ rates. Meanwhile, the COPQ rate is defined by comparing the COPQ with the sales revenue. The feedback loops using discrepancies refer to Vlachos et al. (2007), who constructed a CLD of the forward–reverse supply chain with remanufacturing. In this research, the discrepancy is developed for several decision variables such as serviceable inventory, remanufacturing capacity, collection capacity, and the distributor's actual inventory. These variables are compared to their target or desired values.

The port quality level involves several feedback loops, both positive (reinforcing) and negative (balancing), as follows:

1. **Safety and security loop (Reinforcing 1 or R1)**

   The positive feedback loop comes from extra investment for the safety and security cost to increase the prevention cost, which has an impact on the conformance cost. The higher the conformance cost, the higher the cost of poor quality. The feedback loop is depicted in Figure 30:

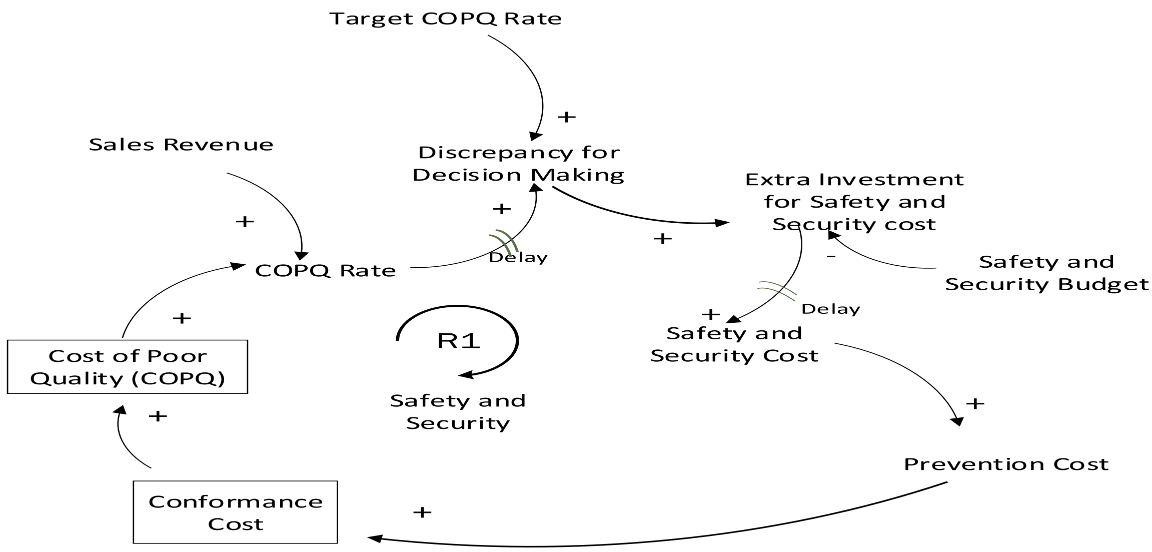


Figure 30. Feedback loop of safety and security

2. **Equipment preventive maintenance (Reinforcing 2 or R2)**

   This positive feedback loop comes from the number of equipment maintenance items to be added, which has an impact on the preventive maintenance cost. The greater the number of maintenance equipment items, the higher the equipment maintenance cost. The feedback loop is seen in Figure 31:

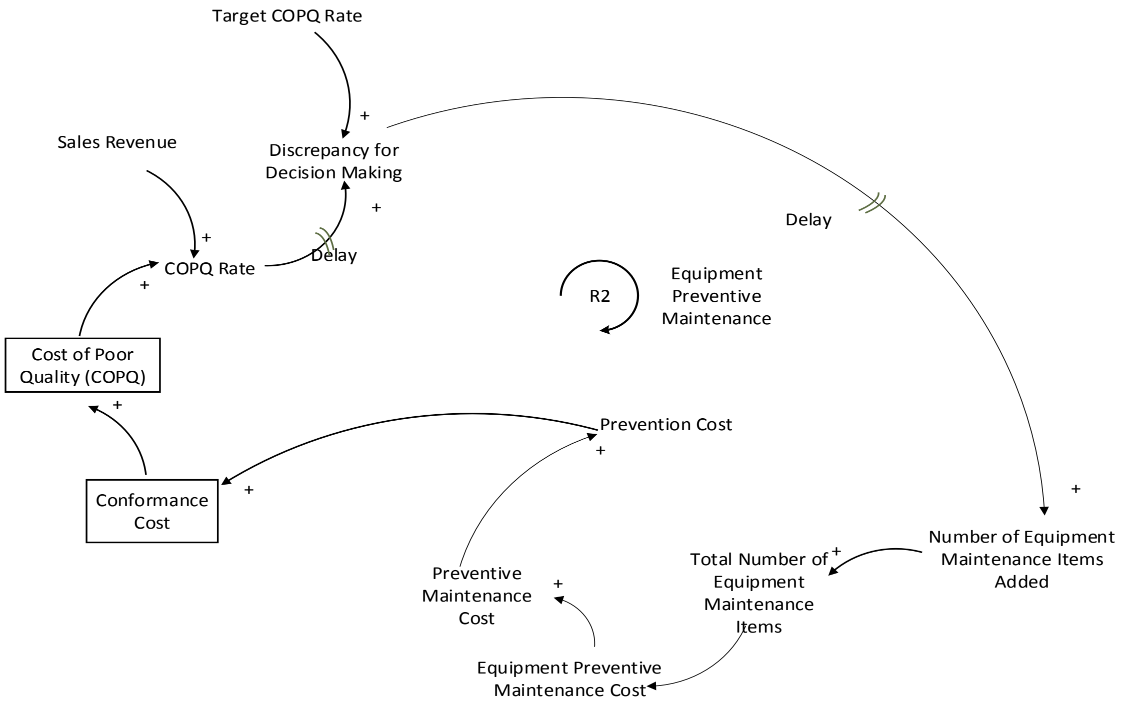


Figure 31. Feedback loop of equipment prevention maintenance

3. **Transporter preventive maintenance (Reinforcing 3 or R3)**

   This positive feedback loop comes from the number of transporter maintenance items to be added, which has an impact on the preventive maintenance cost. The greater the number of transporter maintenance items, the higher the transporter maintenance cost. The feedback loop is shown in Figure 32:

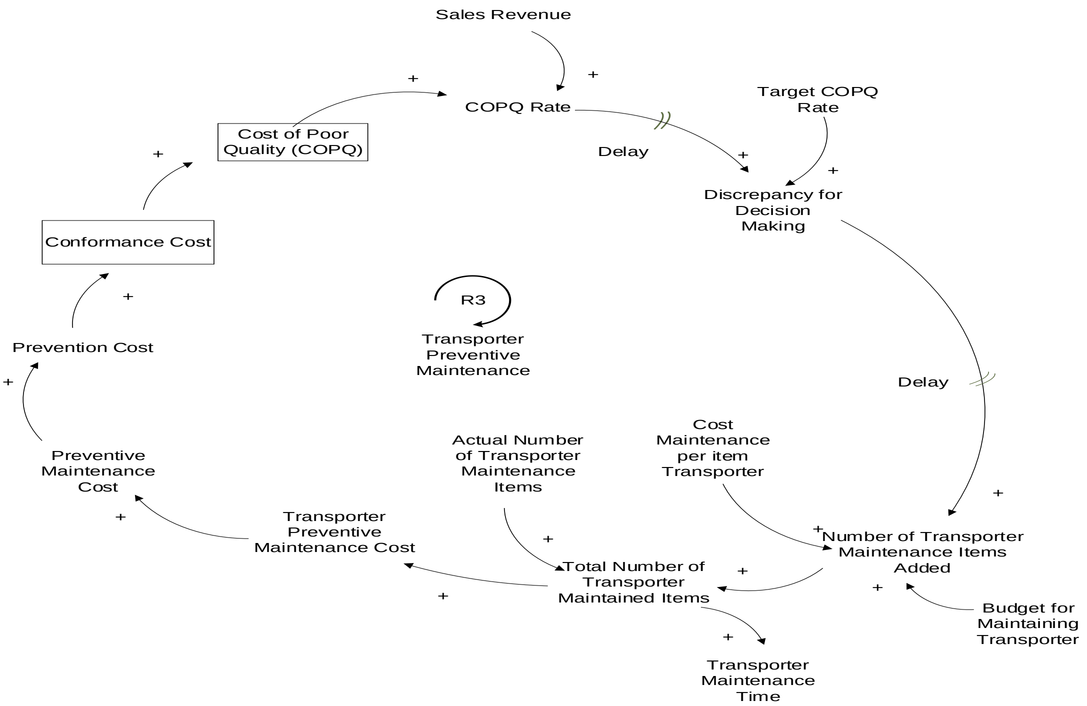


Figure 32. Feedback loop of transporter preventive maintenance

4. **Cargo inspection (Reinforcing 4 or R4)**

This positive feedback loop focuses on the number of added inspectors, which has an impact on the cargo inspection cost. The greater the number of inspectors, the higher the cargo inspection cost. The feedback loop is described in Figure 33:

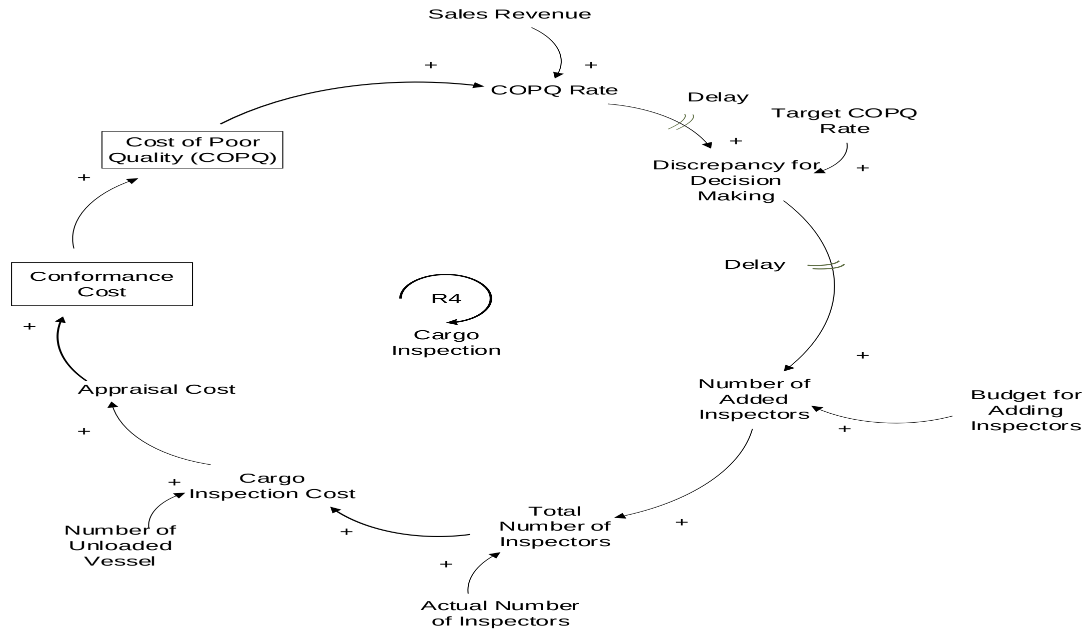


Figure 33. The feedback loop of the cargo inspection

5. **Repair cost due to equipment maintenance (Balancing 1 or B1)**

This negative feedback loop focuses on the number of equipment maintenance items, which influences the repair cost. The greater the number of equipment maintenance items, the lower the repair cost. The feedback loop can be seen in Figure 34:

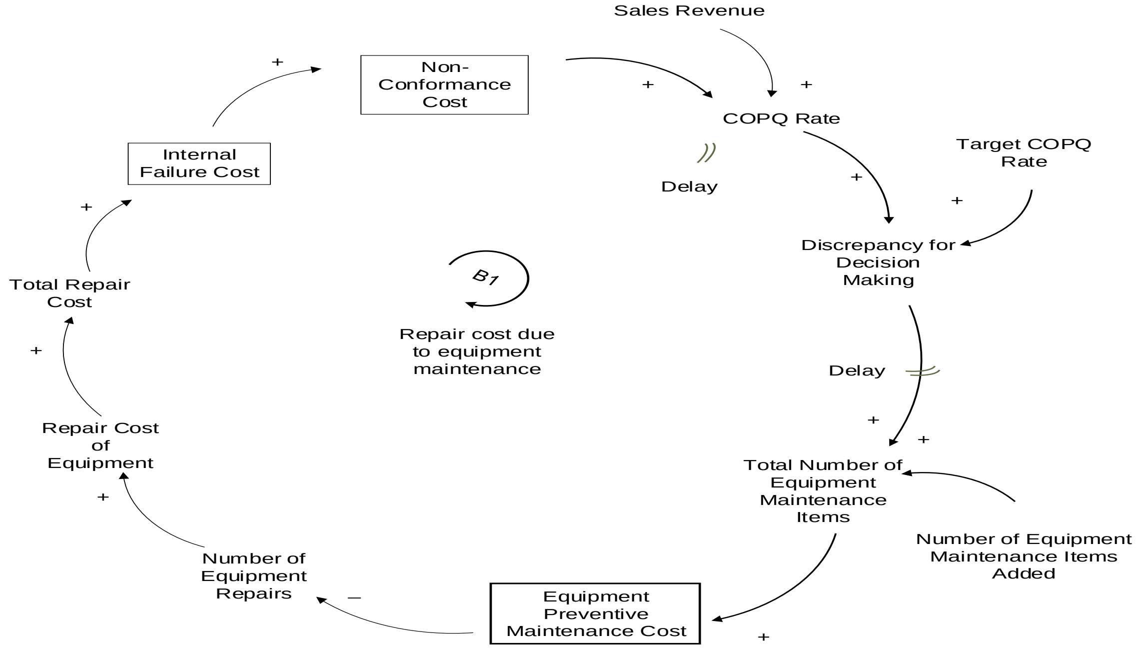


Figure 34. Feedback loop of repair cost due to equipment repair

6. **Repair cost due to transporter maintenance (Balancing 2 or B2)**

   This negative feedback loop focuses on the number of transporter maintenance items, which influences the repair cost. The greater the number of transporter maintenance items, the lower the repair cost. The feedback loop can be seen in Figure 35:

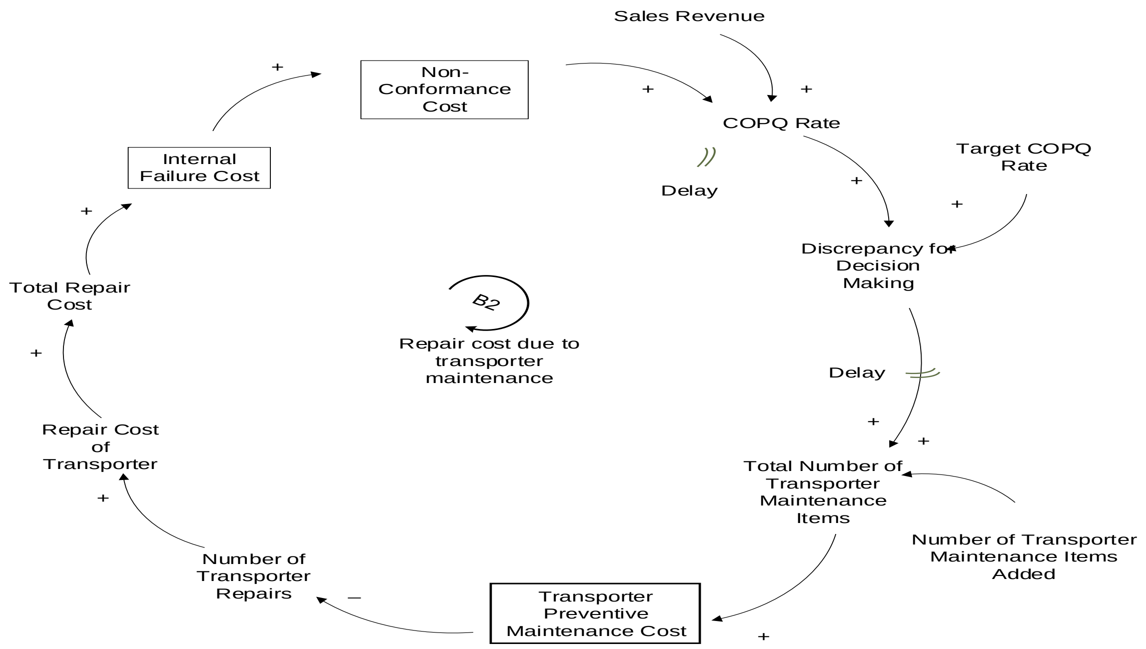


Figure 35. Feedback loop of repair cost due to transporter repair

7. **Delay due to transporter maintenance time (Reinforcing 5 or R5)**

   This positive feedback loop focuses on the transporter maintenance time, which influences the total delay time. The longer the transporter maintenance time, the longer the total delay time. The feedback loop can be seen in Figure 36:

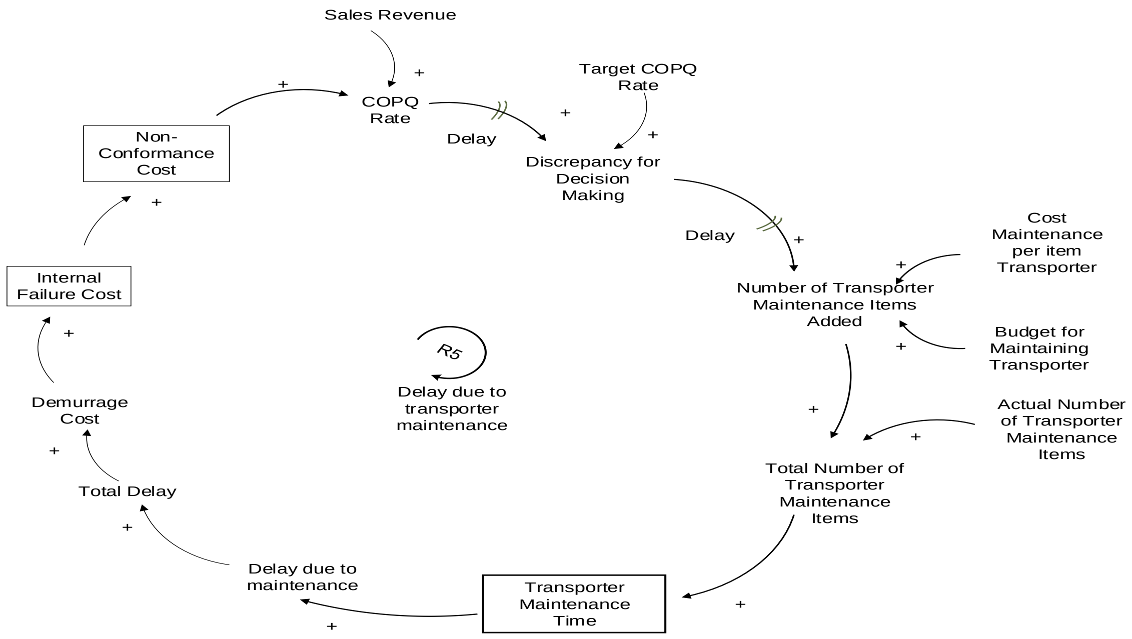


Figure 36. Feedback loop of delay due to transporter maintenance

8. **Delay due to equipment maintenance time (Reinforcing 6 or R6)**

This positive feedback loop focuses on the equipment maintenance time, which influences the total delay time. The longer the equipment maintenance time, the longer the total delay time. The feedback loop can be observed in Figure 37:

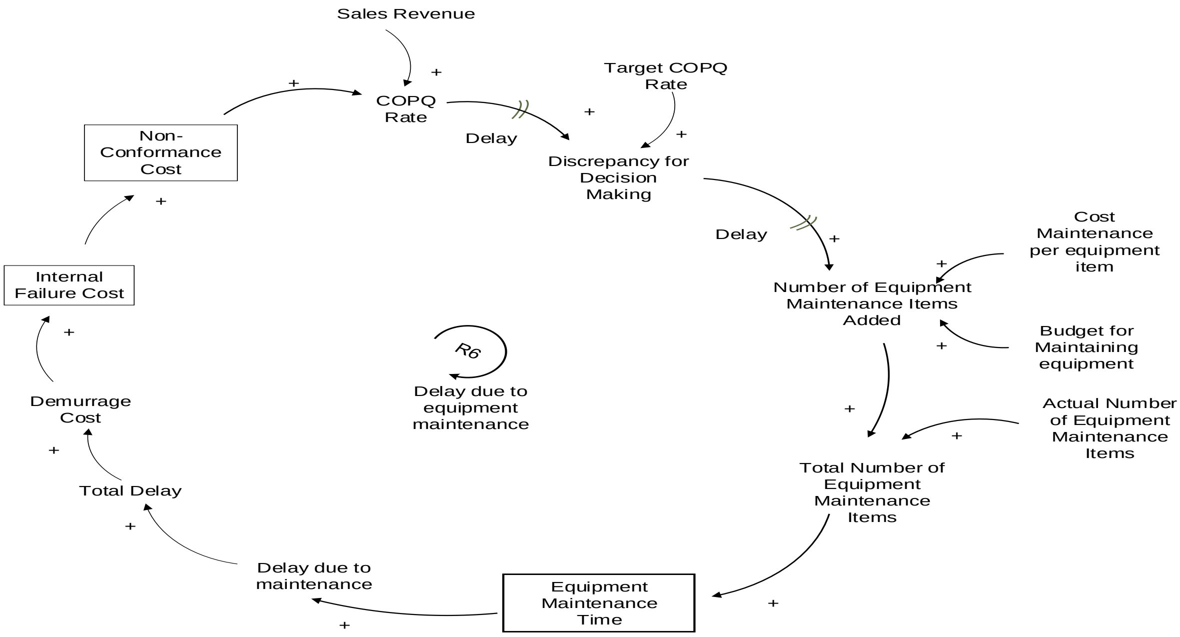


Figure 37. Feedback loop of delay due to equipment maintenance

9. **Delay due to transport repair (Balancing 3 or B3)**

This negative feedback loop focuses on the number of transporter maintenance items, which influences the total delay time. The greater the number of transporter maintenance items, the lower the number of transporter repairs. The lower of number of transporter repairs influences the shorter of the transporter repair time. The shorter the transporter repair time, the shorter the total delay time. The feedback loop can be seen in Figure 38:

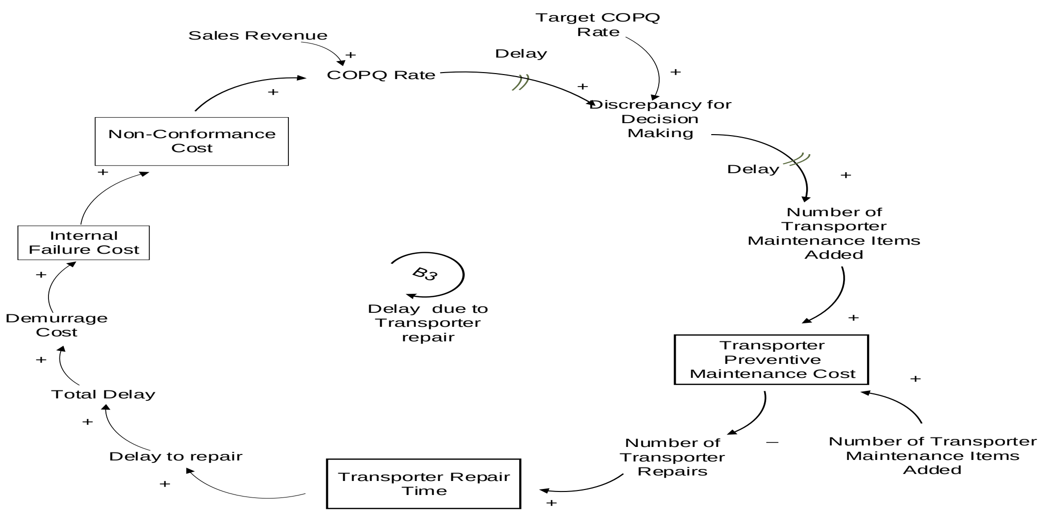


Figure 38. Feedback loop of delay to transport repair

10. Delay due to equipment repair (Balancing 4 or B4)

This negative feedback loop focuses on the number of equipment maintenance items, which influences the total delay time. The greater the number of equipment maintenance items, the lower the number of equipment repairs. The lower of number of equipment repairs influences the shorter of the equipment repair time. The shorter the equipment repair time, the shorter the total delay time. The feedback loop can be checked in Figure 39:

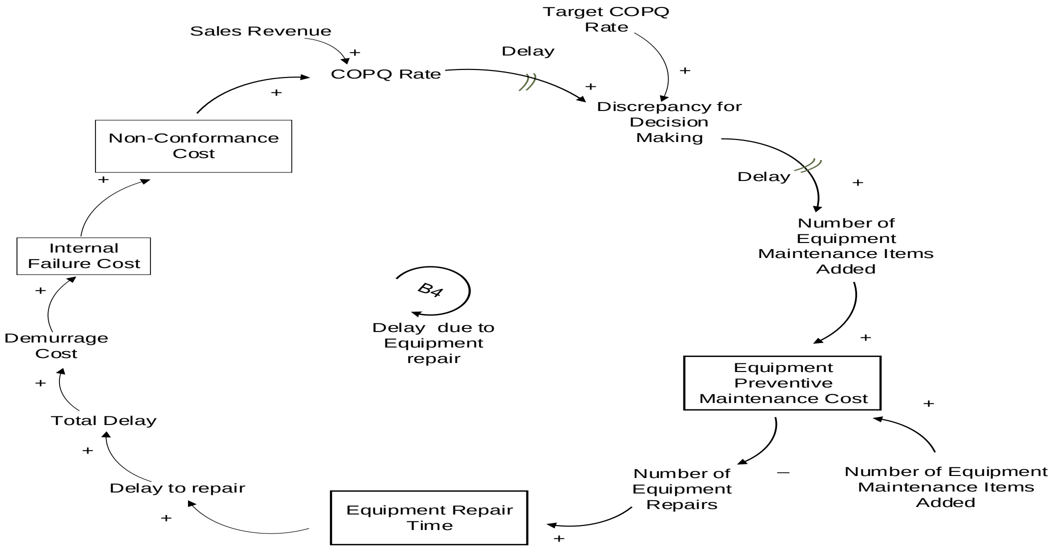


Figure 39. Feedback loop of delay to equipment repair

11. Damage due to cargo inspection (Balancing 5 or B5)

This negative feedback loop focuses on the cargo inspection cost, which influences the internal failure cost. The higher the cargo inspection cost, the lower the internal failure cost. The feedback loop can be observed in Figure 40:

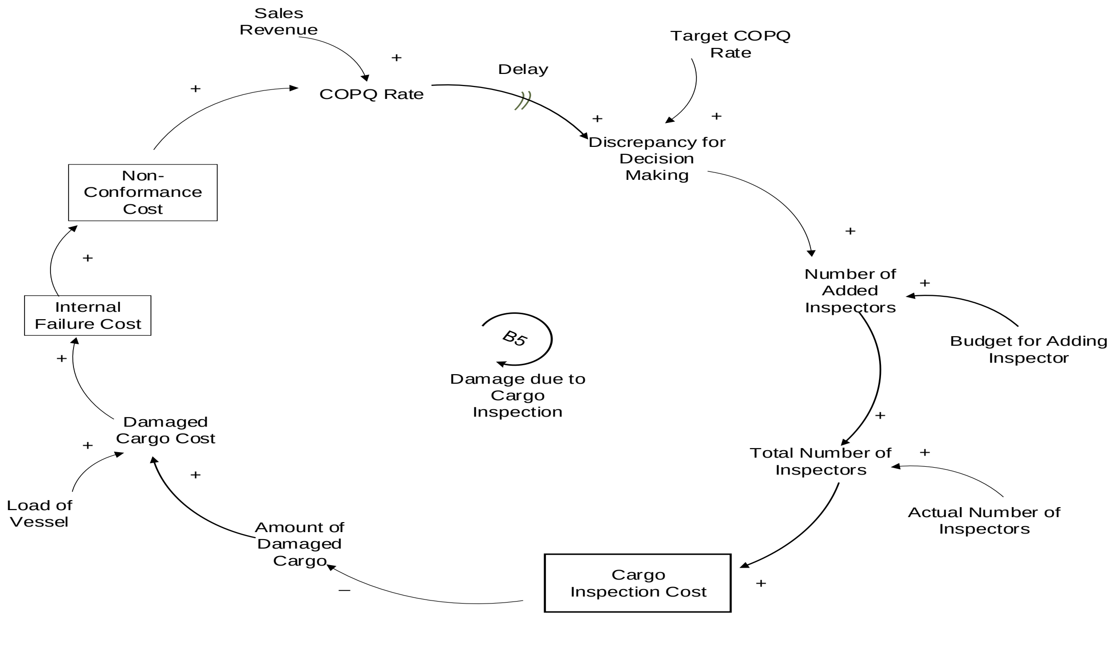


Figure 40. Feedback loop of damage due to cargo Inspection

12. Damage due to safety and security cost (Balancing 6 or B6)

This negative feedback loop focuses on the safety and security cost, which influences the internal failure cost. The higher the safety and security cost, the lower the internal failure cost. The feedback loop can be observed in Figure 41:

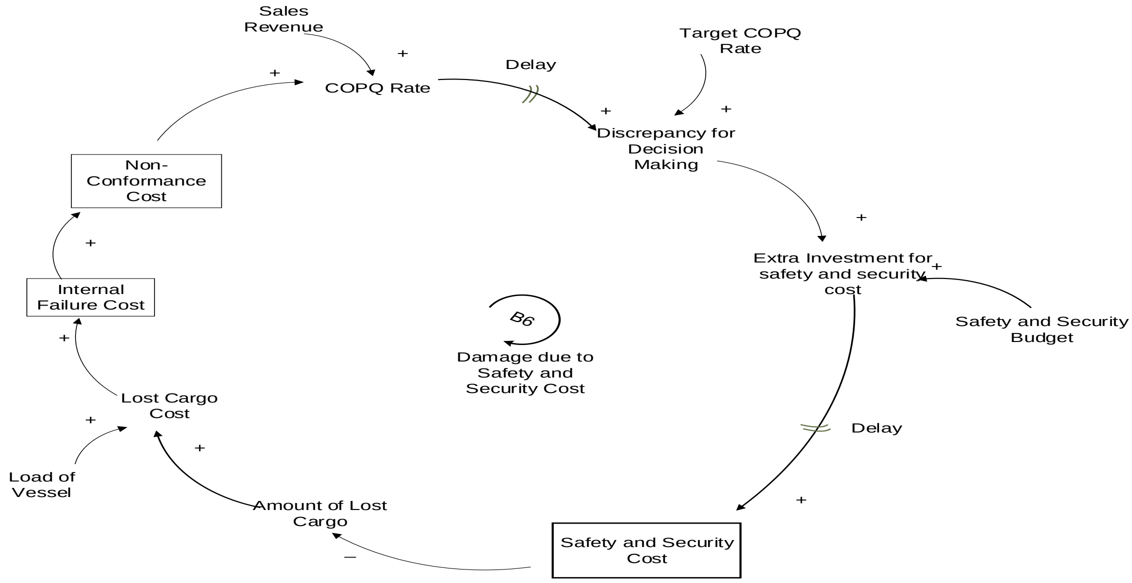


Figure 41. Feedback loop of damage due to safety and security cost

13. Compensation cost due to delay of repair (Balancing 7 or B7)

This negative feedback loop focuses on the number of equipment and transporter maintenance items, which influences the opportunity cost. The greater the number of equipment and transporter maintenance items, the lower the repair time of equipment and transporter. The lower the repair time of equipment and transporter, the shorter the delay due to repair. The shorter the delay due to repair, the lower the opportunity cost. The feedback loop can be observed in Figure 42:

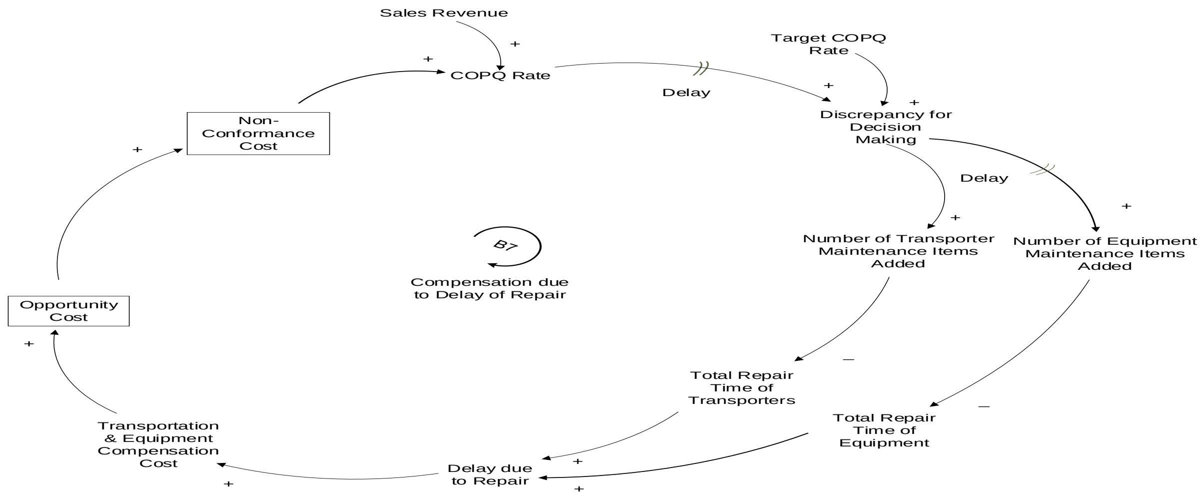


Figure 42. CLD of compensation due to delay of repair

14. Compensation cost due to delay of maintenance (Reinforcing 7 or B7)

This positive feedback loop focuses on the number of equipment and transporter maintenance items, which influences the opportunity cost. The greater the number of equipment and transporter items, the higher the maintenance time of equipment and transporter. The higher the maintenance time of equipment and transporter, the higher the delay due to repair. The higher the delay due to repair, the higher the opportunity cost. The feedback loop can be observed in Figure 43:

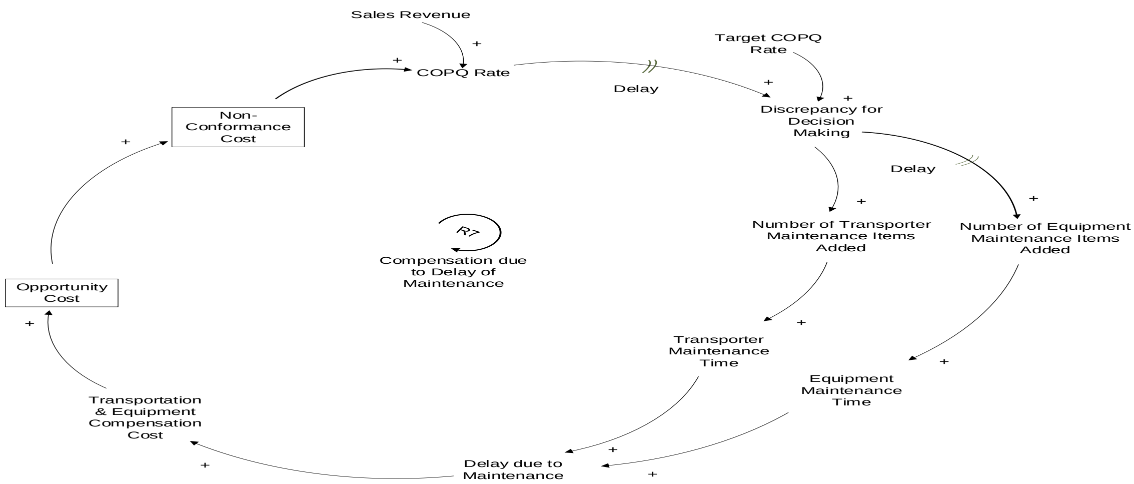


Figure 43. CLD of compensation due to delay of maintenance

15. Compensation cost due to lost and damaged cargo (Balancing 8 or B8)

This negative feedback loop focuses on the safety and security cost and cargo inspection cost, which influences the opportunity cost. The greater the safety and security cost and cargo inspection cost, the lower the amount of lost cargo and the number of damaged cargo. The less lost and damaged cargo there is, the lower the opportunity cost. The feedback loop can be observed in Figure 44:

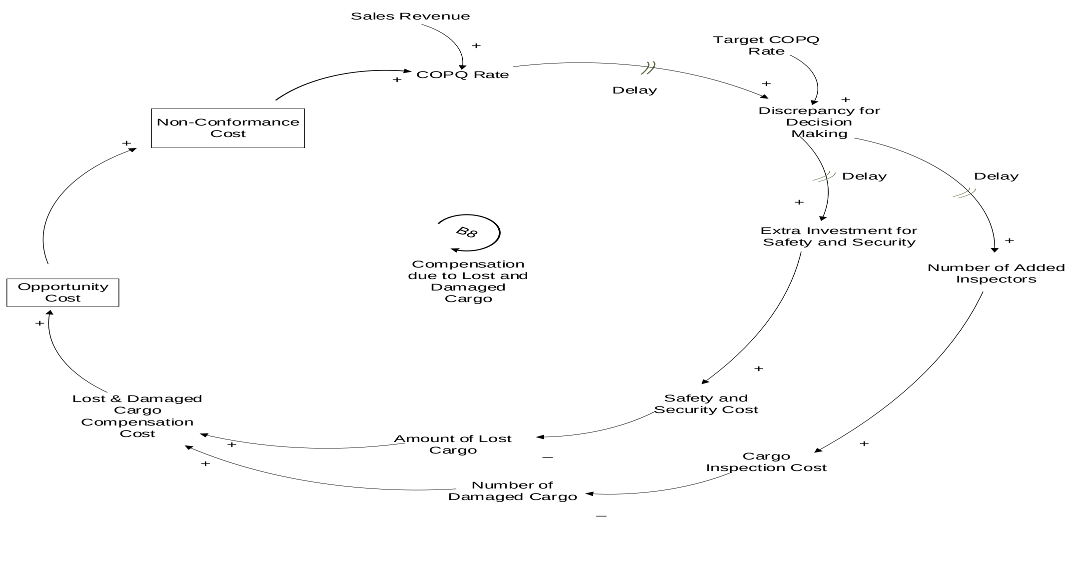


Figure 44. CLD of Compensation due to lost and damaged cargo

4.6.3 The Port Performance Metrics

The CLD of the port performance metrics consists of the sigma value and the process capability indices of lost and damaged cargo, equipment and transporter damage, and equipment and transporter delay time. The CLD of the sigma value of lost and damaged cargo can be viewed in Figure 45:

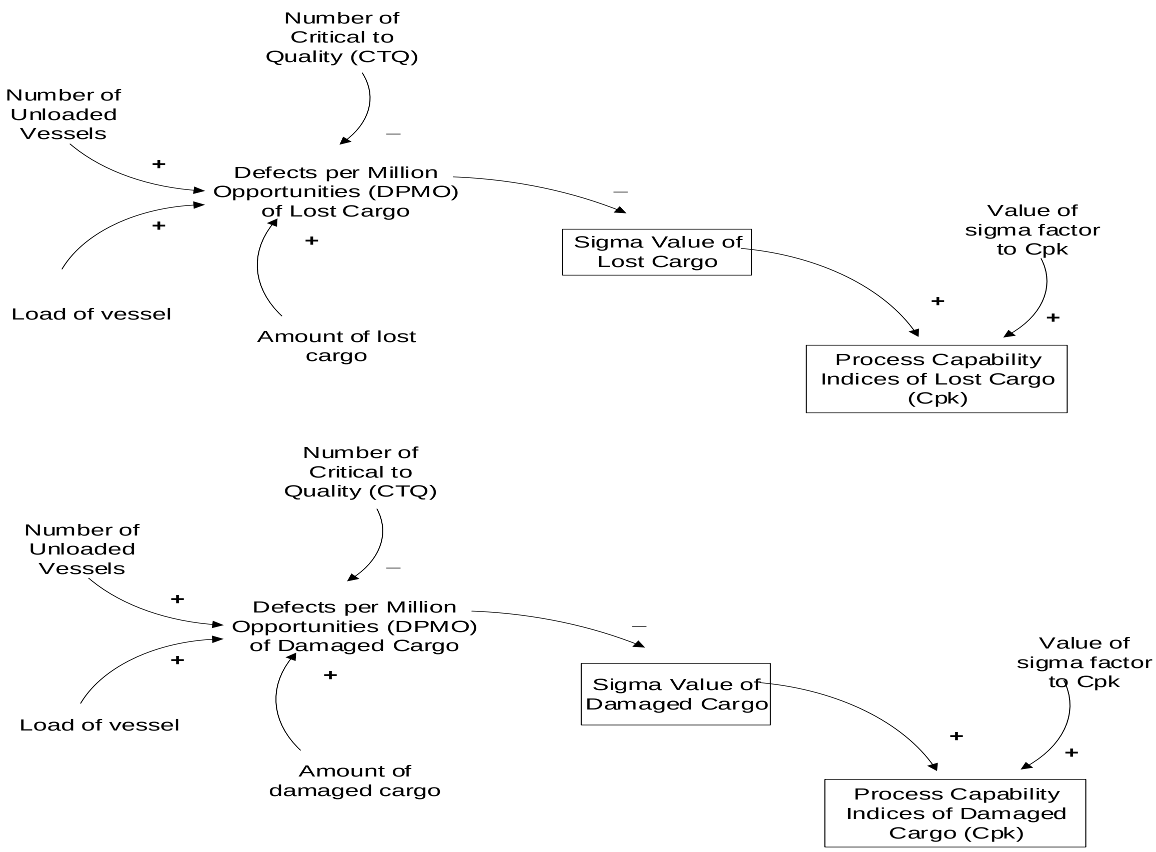


Figure 45. CLD of sigma value of lost and damaged cargo

The amount of lost cargo and damaged cargo and the vessel load influence the defects per million opportunities (DPMO). The less the DPMO of lost and damaged cargo, the greater the sigma value and process capability indices of lost and damaged cargo. The total equipment and transporter repair time compared with the available time of the equipment influences the DPMO of transporter and equipment breakdown. The less the DPMO of transporter and equipment breakdown, the greater the sigma value and process capability indices of transporter and equipment breakdown. The CLD of transporter and equipment breakdown can be observed in Figure 46:

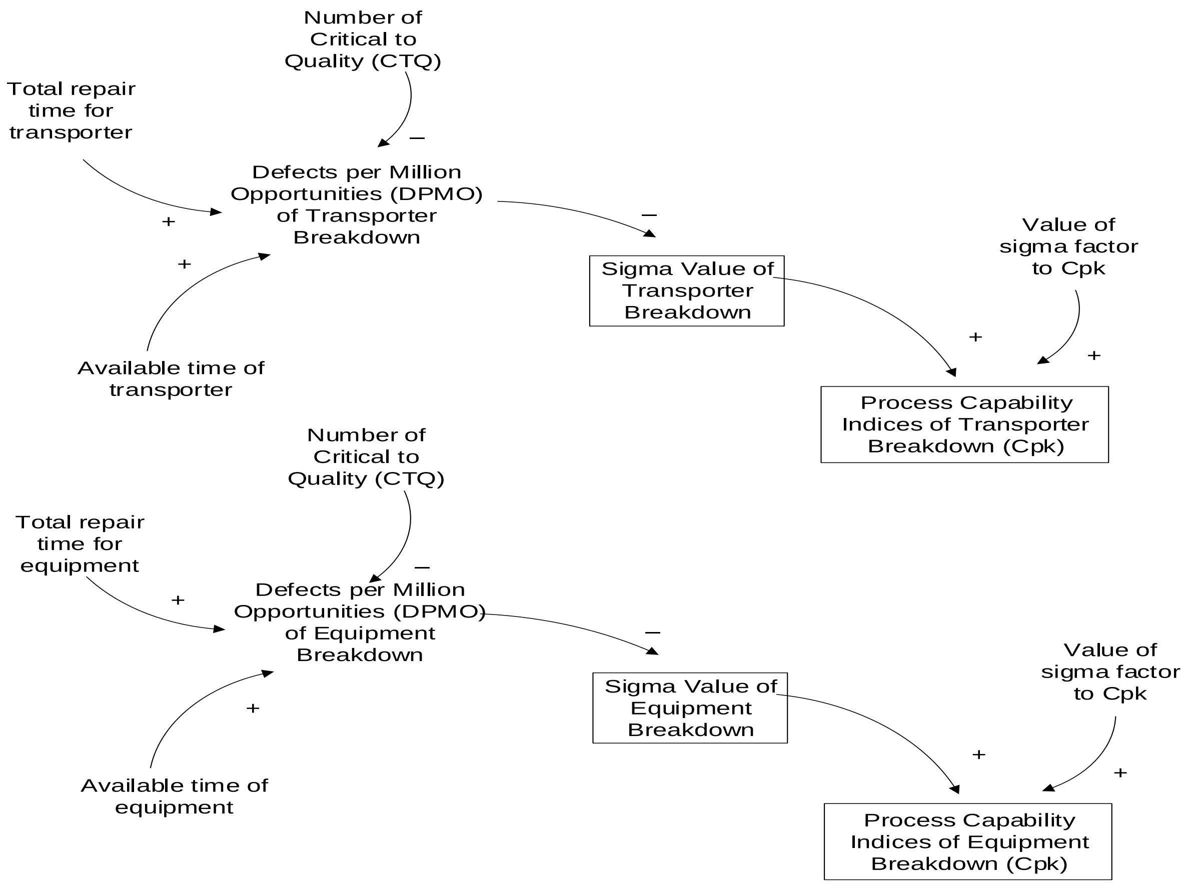


Figure 46. CLD of sigma value of equipment and transporter breakdown

The total delay time relates to defects so it can be measured as the defects per million opportunities (DPMO). The delay time compared to the service time influences the DPMO of the delay time. The less the DPMO, the greater the sigma value and the process capability indices of delay time, as indicated in Figure 47 below:

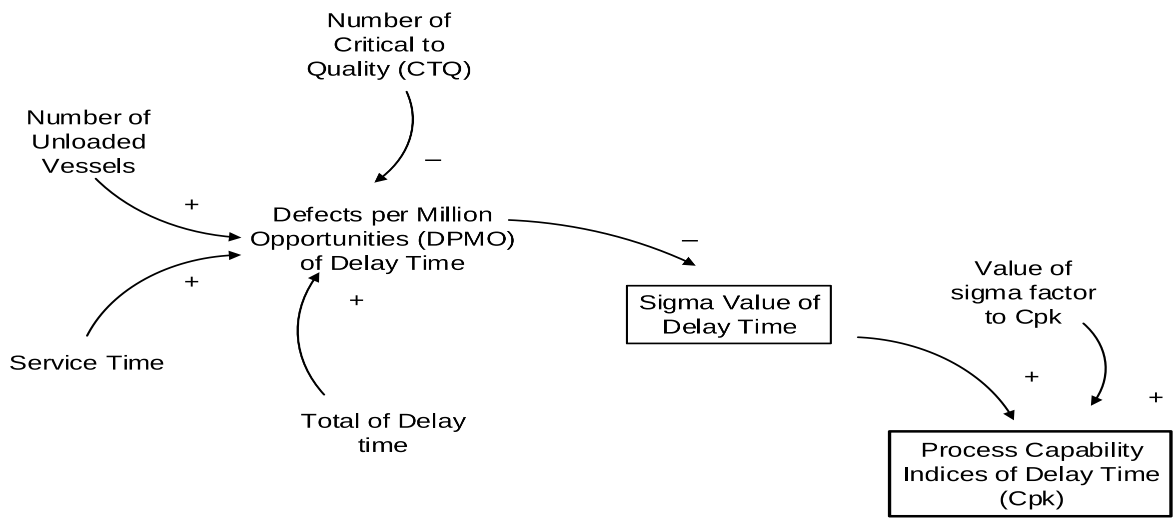


Figure 47. CLD of sigma value of delay time

Chapter 5

System Dynamics with the Stock Flow Diagram

The stock flow diagram (SFD) is required to simulate the model that is generated from the causal loop diagram in Chapter 4.

5.1 The Stock Flow Diagram (SFD)

The stock flow diagram for this model is simulated using Powersim software. The variables that are included in the software model represent the causal relationships that are drawn in causal loop diagram, complete with their formulation. The SFD of the six sigma model in ports can be examined in Appendix B. This SFD consists of three sub-systems: the port operation, the port quality level and the port performance metrics.

5.1.1 The Port Operation

The SFD of the port operation consists of three sub-systems, referring to the causal loop diagram of the port operation, namely the sea side, the land side, and the port operation performance.

1. **Sea side**

   Firstly, fully loaded vessels will be brought to the port terminal by tugboats and moored to available berths. After the vessels are berthed securely, the cranes available at the berths start to discharge their loads. The time required to bring the vessels in depends on the tugboat productivity, which is influenced by the tugboat capacity and the number of cycles of tugboat operations, as can be seen in Figure 48 below:

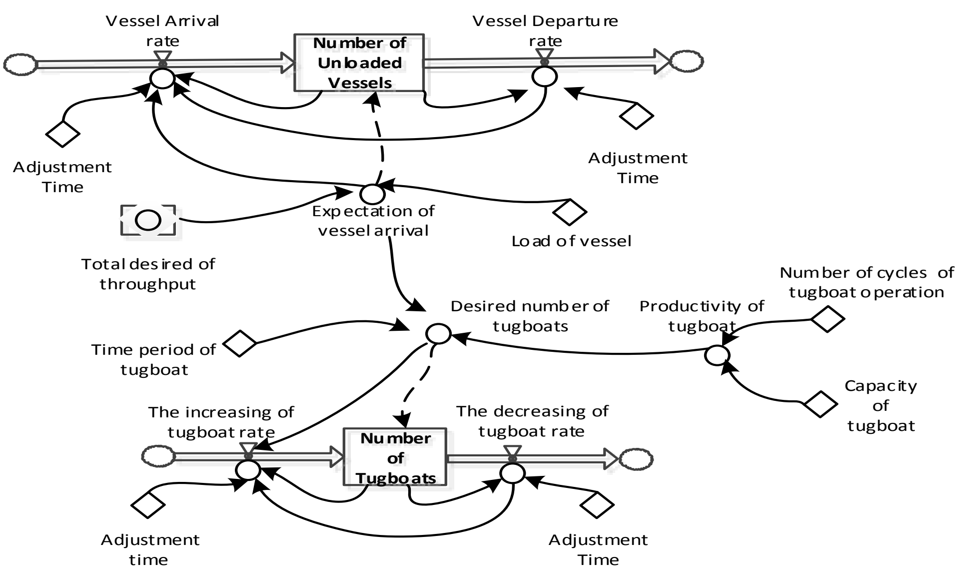


Figure 48. SFD of the sea side in the port operation

2. **Land Side**

The SFD of the land side involves the activities of the crane to discharge the load of the vessel as depicted in Figure 49. The time required to unload the vessels depends on the crane productivity, which is influenced by the crane capacity and the operating cycle of the crane. Then, the load of the vessels is directly loaded to the intermodal connectivity, which utilizes trucks and conveyor belts. The capacity of the trucks and conveyor belt must be balanced with the cranes' productivity to transfer the vessel loads. The truck productivity is influenced by the truck capacity and the number of cycles of truck operation, whereas the conveyor productivity is influenced by the conveyor capacity and the length of the conveyor. The commodities are shipped to the customers via storage in the buffer warehouse and the stockpile yard at the port or directly to the destination warehouse and the stockpile yard of the customer.

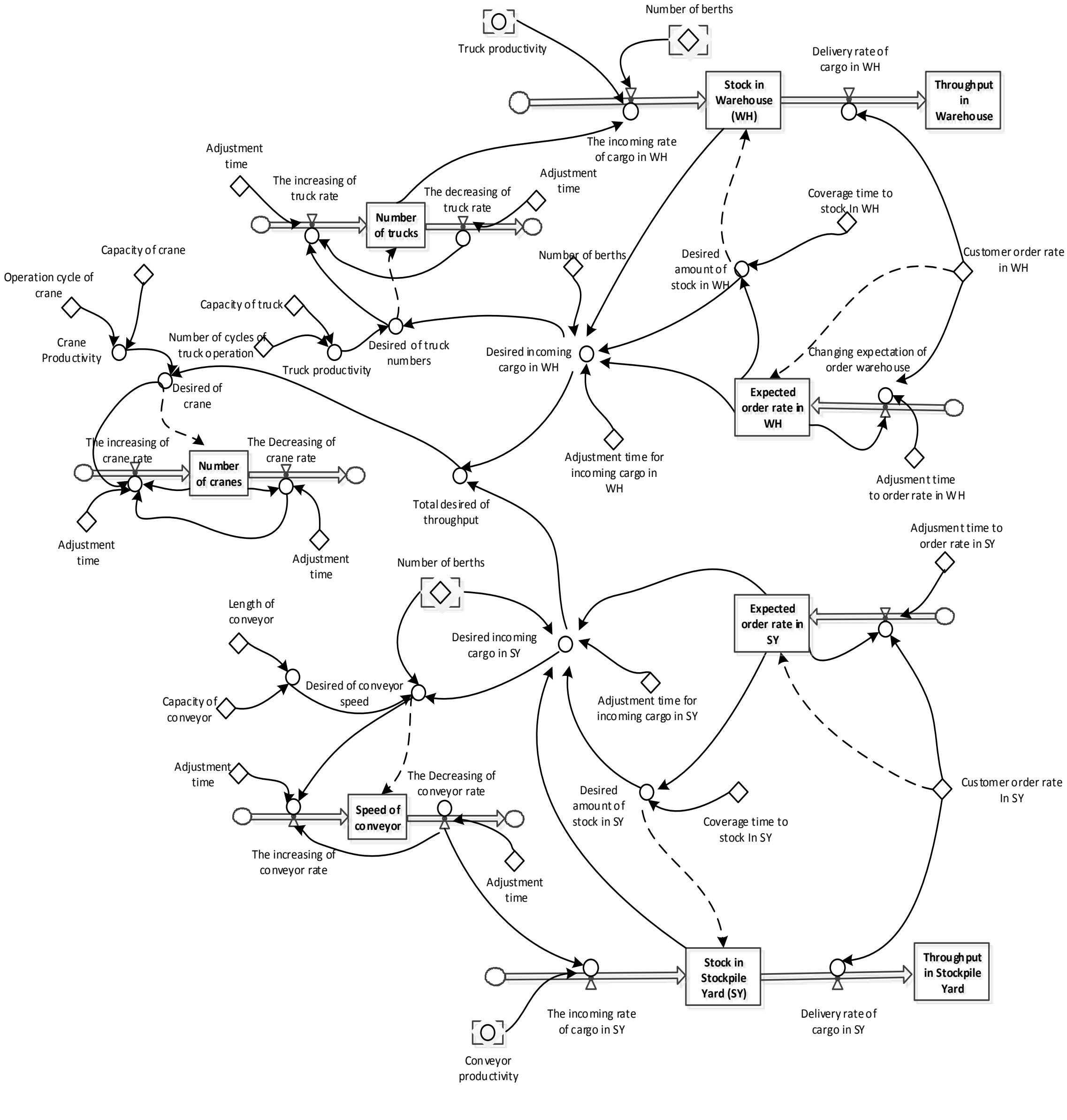


Figure 49. The SFD of the land side in the port operation

3. **Port Operation Performance**

The SFD consists of the performance indicators for the port operation as depicted in Figure 50. The approach time indicates the time required to bring the vessel into the port terminal. Meanwhile, the berthing time means the time needed to discharge the vessels' load. The service time is the total time starting from the vessels' arrival at the port terminal until the vessels leave again, or with the addition of the approach time and berthing time. The value of the berth occupancy ratio (BOR) indicates the occupancy of berths in the port, which is influenced by the service time, the number of unloaded vessels, the number of berths, and the available time at the berths. The BOR value influences the vessel waiting time. The higher the BOR, the longer the vessel waiting time, which causes congestion of the vessels.

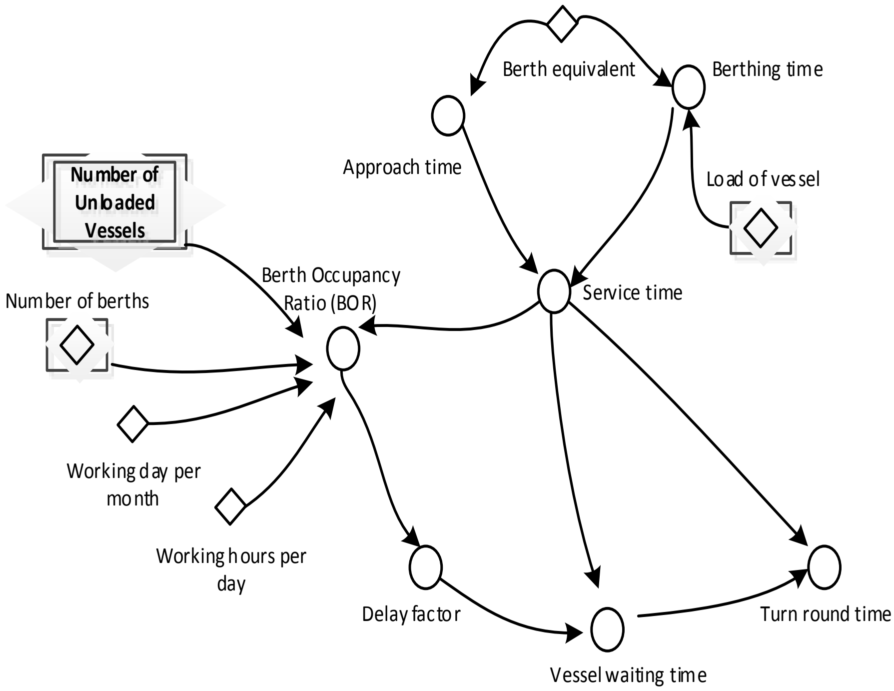


Figure 50. SFD of the land side in the port operation

5.1.2 The Port Quality Level

The stock flow diagram (SFD) of the port quality level consists of the conformance cost, the non-conformance cost, and the opportunity cost, which together establish the cost of poor quality (COPQ) as shown in Figure 51. The SFD of the port quality level can be seen in Appendix B, along with the conformance cost, the non-conformance cost, and the opportunity cost. The comparison of the COPQ with the sales revenue is required to determine the appropriateness of the COPQ. A feedback loop is constructed with the calculation of the gap between the desired and target COPQ rate.

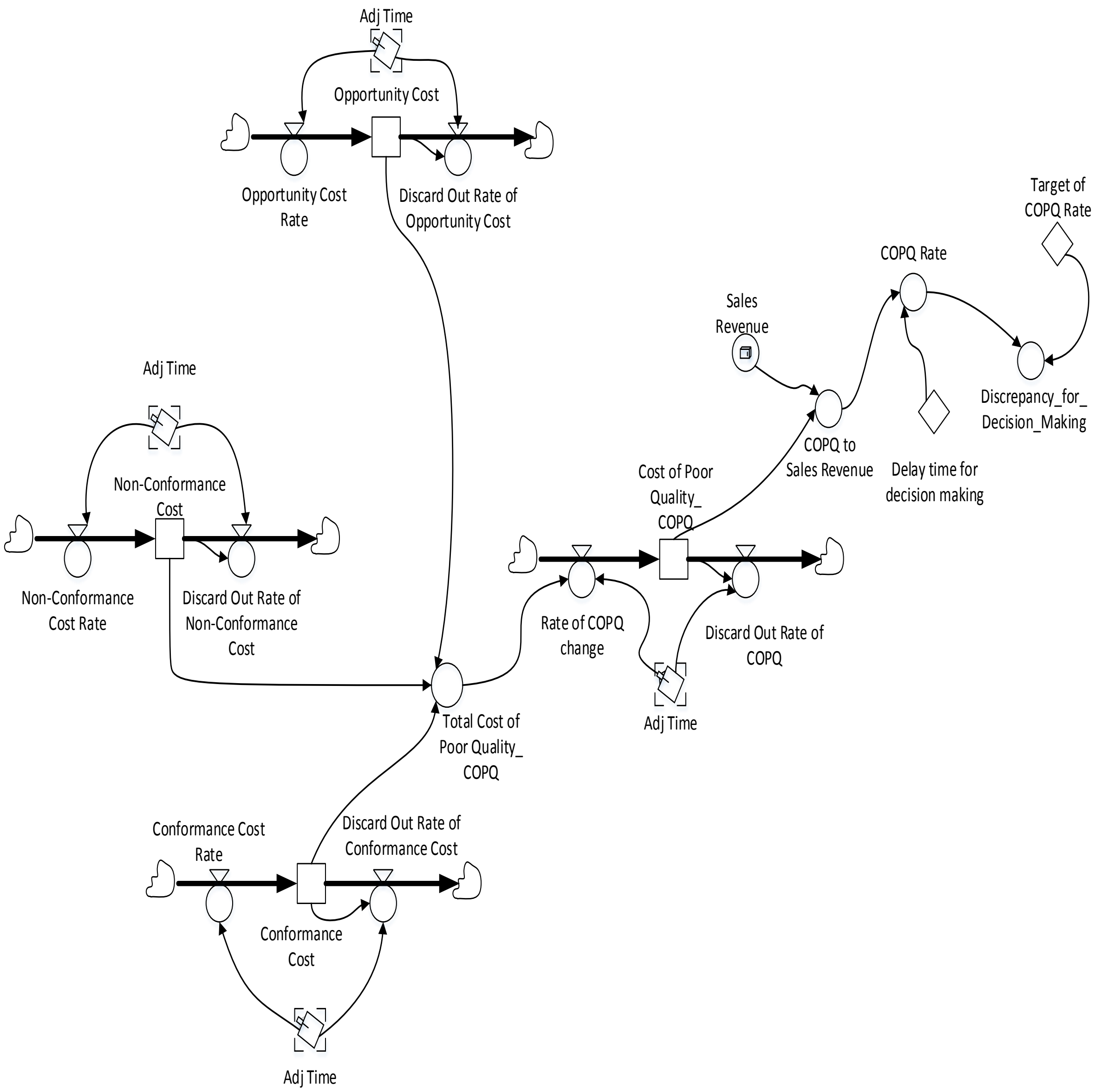


Figure 51. The SFD of the cost of poor quality (COPQ)

The conformance cost involves the rate of the total prevention and appraisal cost. The prevention cost involves the costs that come from preventive maintenance costs for transporters and equipment, the safety and security cost, recruiting cost, quality engineering cost, worker training cost, and marketing research cost. The SFD of the prevention cost can be seen in detail in Appendix B. Meanwhile, the appraisal cost involves the costs of checking of the equipment and transporters, the cargo inspection cost, customs clearance cost, quality audit cost, draft survey cost, and quality audit cost. The SFD of the appraisal cost can be seen in detail in Appendix B. The non-conformance cost comes from the rate of internal failure cost and the external failure cost. The internal failure cost involves the repair cost, demurrage cost, the lost cargo cost, and the damage cost. The internal failure cost, in general, can be seen in Figure 52:

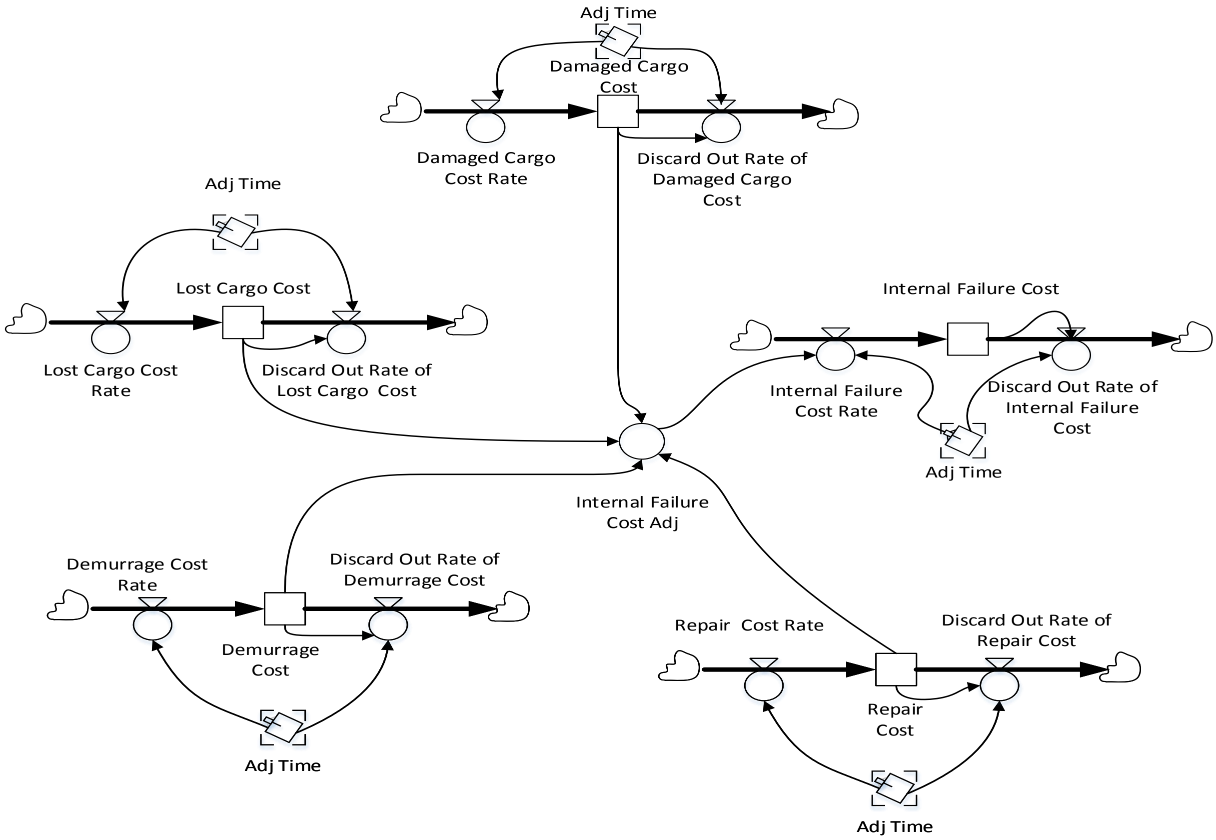


Figure 52. SFD of internal failure cost

The SFD of the internal failure cost can be seen in detail in Appendix B. Meanwhile, the external failure cost involves the complaint adjustment cost and discount to damage cost as shown in Figure 53:

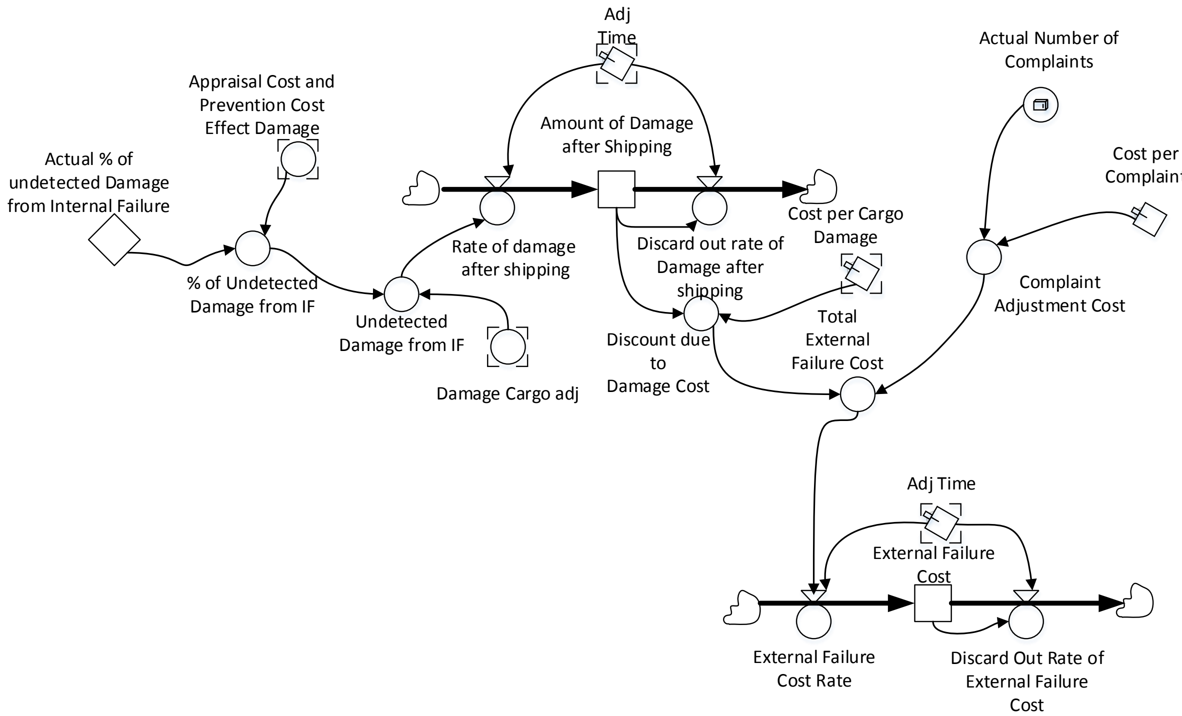


Figure 53. SFD of external failure cost

According to Kiani et al. (2009), when both the prevention and appraisal costs increase simultaneously this will reduce the failure cost and the total cost of quality. Increase of the appraisal and prevention costs will have the effect of decreasing the internal failure cost. The prevention cost, comprising the cost of preventive maintenance of equipment and transporters, has the effect of decreasing the internal failure cost arising from the repair cost, as can be seen in Figure 54:

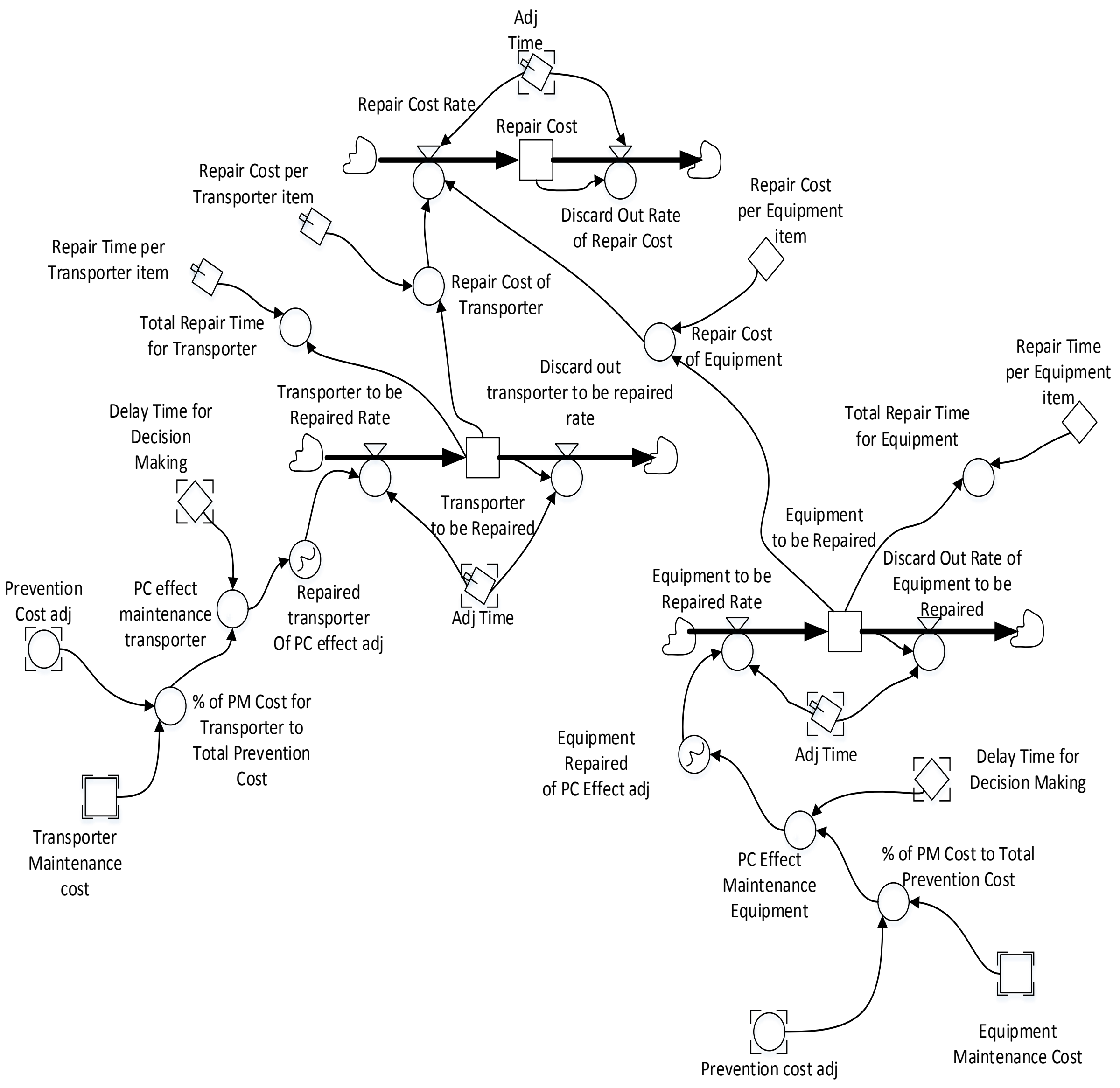


Figure 54. SFD of the impact of prevention cost on the repair cost

Furthermore, the prevention and appraisal costs have the effect of decreasing the lost and damaged cargo cost. The SFD of the prevention cost through the safety and security cost and the appraisal cost through the cargo inspection cost can be seen in Figure 55:

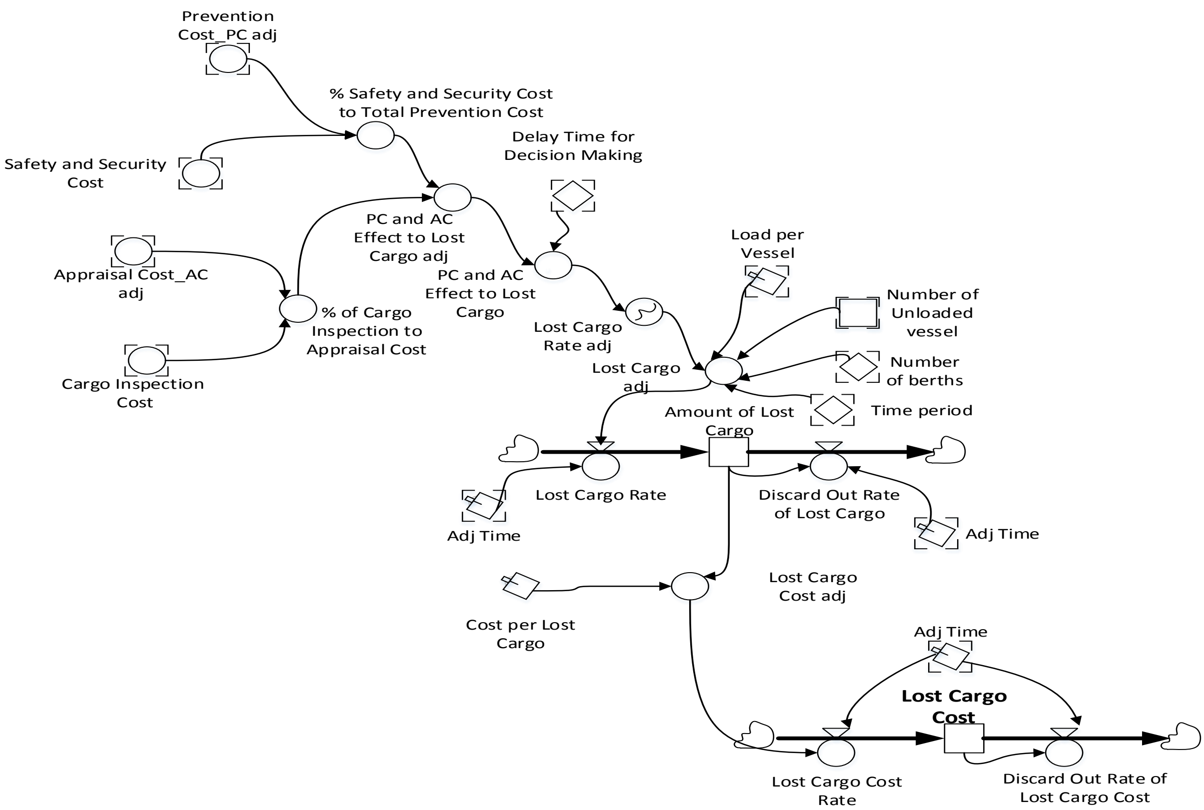


Figure 55. SFD of the effect of prevention and appraisal cost on the lost cargo cost

The same effect of the prevention and appraisal cost on the damaged cargo cost is decreasing. Also, the equipment maintenance time and the transporter maintenance time in prevention activity will have an impact on the delay time, which influences the demurrage cost. Besides that, the repair time of equipment and transporters will also have an impact on the delay time, which affects the demurrage cost. This SFD is shown in Figure 56:

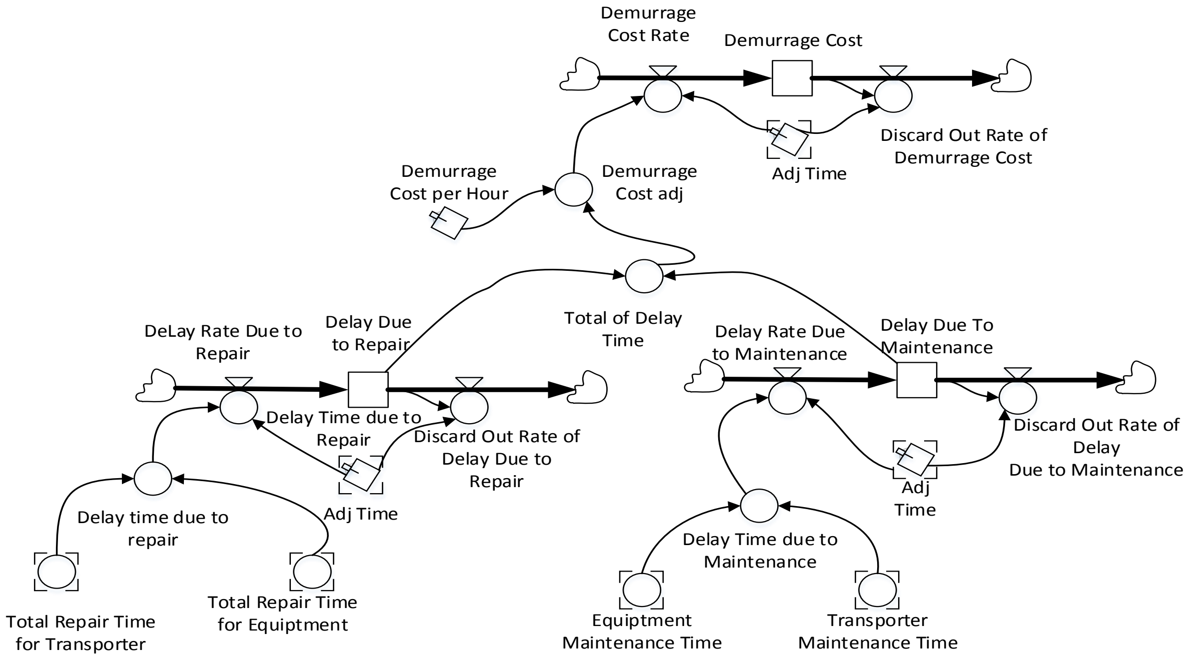


Figure 56. SFD of the effect of equipment and transporter delay time on the demurrage cost

The feedback loop from the discrepancy between the cost of poor quality (COPQ) compared with the sales revenue and the target COPQ is obtained through the prevention and appraisal cost. This discrepancy is expressed in Figure 51, page 56. The feedback through the prevention cost is performed by adding the safety and security cost, and adding the number of transporter and equipment maintenance items. The SFD can be seen in Figure 57:

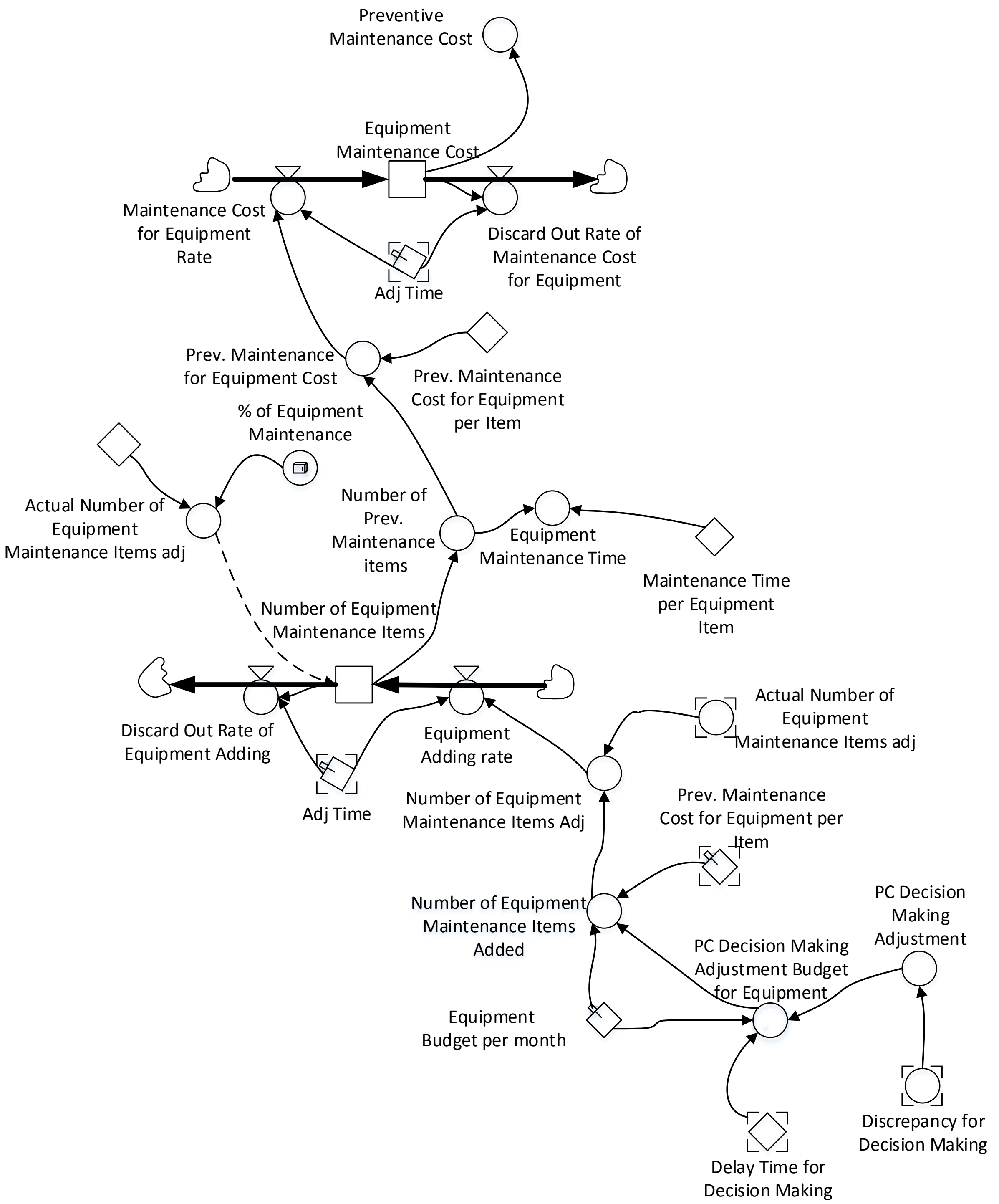


Figure 57. Feedback loop from the COPQ to preventive maintenance cost

There is the same pattern for the feedback loop from the COPQ to the preventive transporter maintenance cost. Thus the feedback of the COPQ to the safety and security cost can be seen in Figure 58 below:

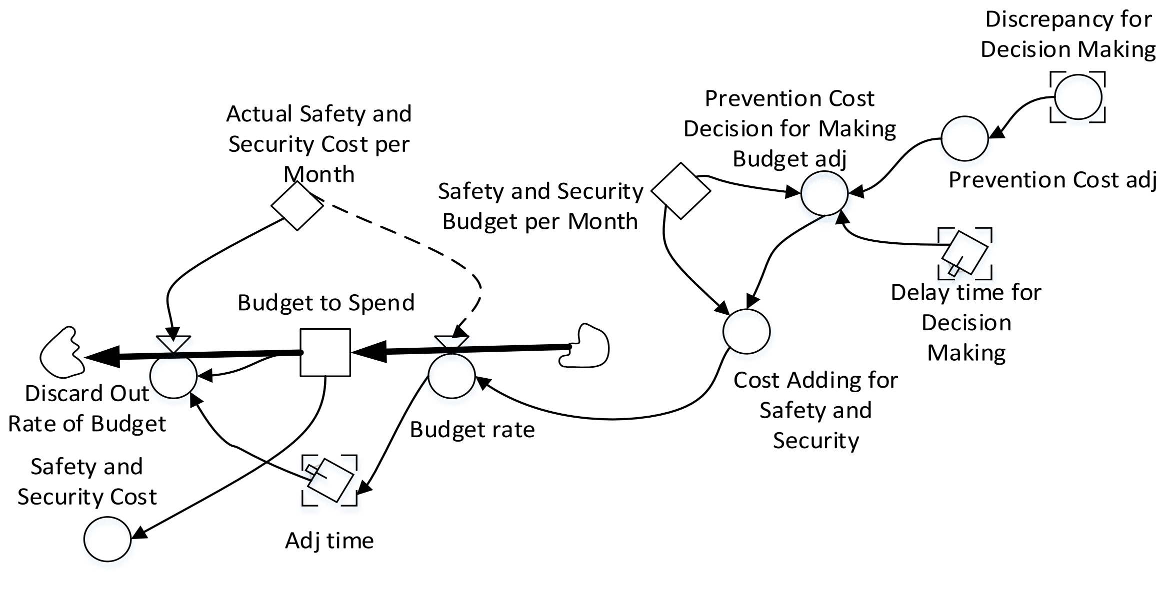


Figure 58. Feedback loop from the COPQ to safety and security cost

Meanwhile, the feedback loop through the appraisal cost is performed by increasing the number of inspectors. The SFD can be seen in Figure 59:

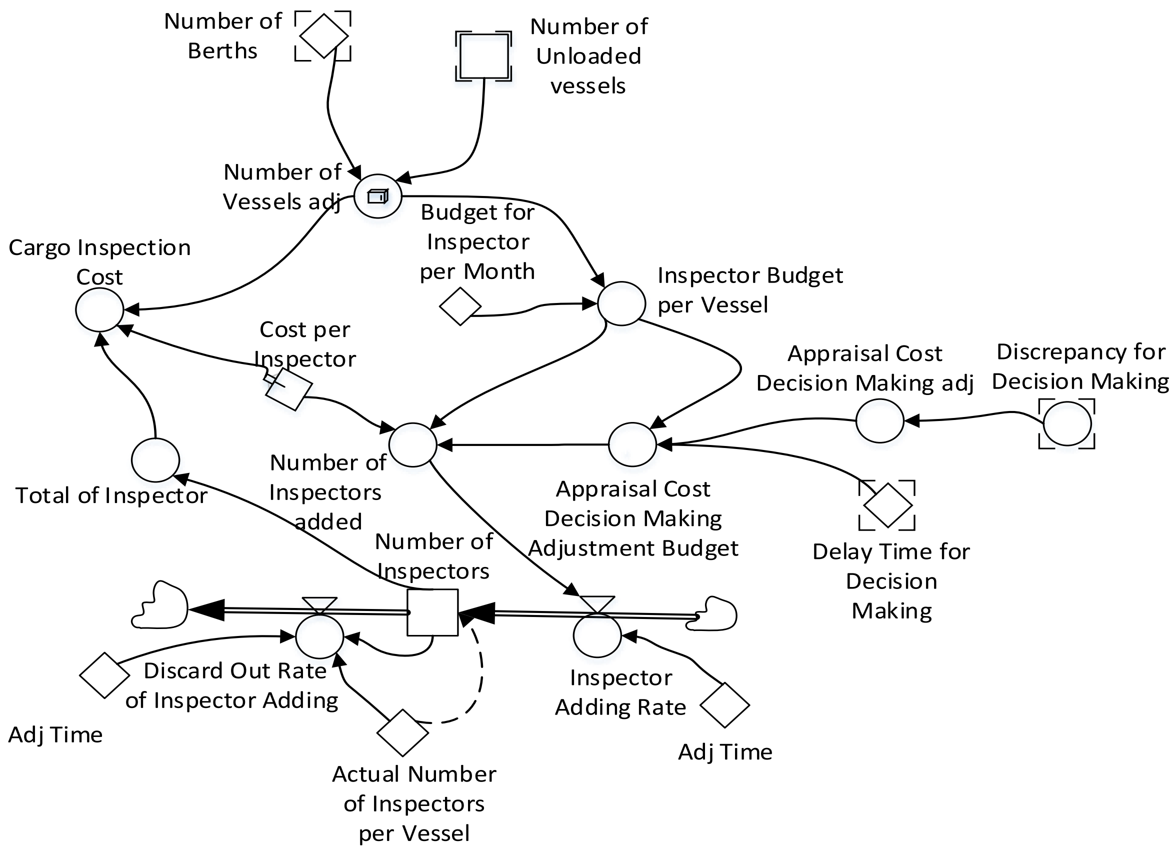


Figure 59. Feedback loop from the COPQ to cargo inspection cost

5.1.3 The Port Performance Metrics

The SFD of the performance metrics based on the causal loop diagram in Chapter 4 involves measurement of the sigma value and process capability indices. All the performance metrics are measured for the internal failures that happen in the port. The sigma value and process capability indices are measured for the lost cargo, damaged cargo, equipment and transporter breakdown, and the equipment and transporter delay time. All failures have an effect on the internal failure cost. In this research, all defects per million opportunities (DPMO) are measured in the whole supply chain and focused on the sources of waste in the cargo handling process at the port. The SFD of the sigma value and process capability indices for lost cargo and damaged cargo can be seen in Figure 60:

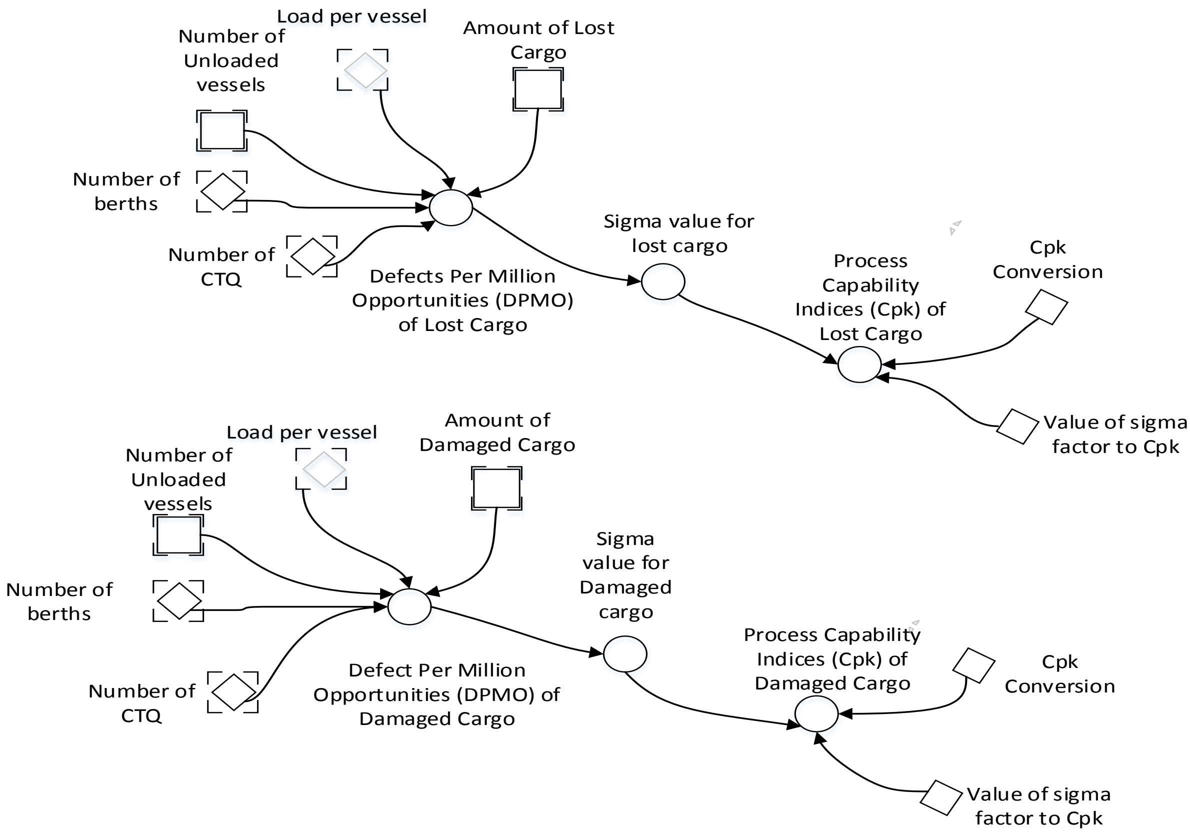


Figure 60. SFD of sigma value and process capability indices of lost and damaged cargo

The lost and damaged cargo contributes to increasing the lost and damaged cargo costs, which are components of the internal failure cost. The equipment and transporter breakdown are measured in the equipment and transporter repair time. The SFD of equipment and transporter breakdown is shown in Figure 61:

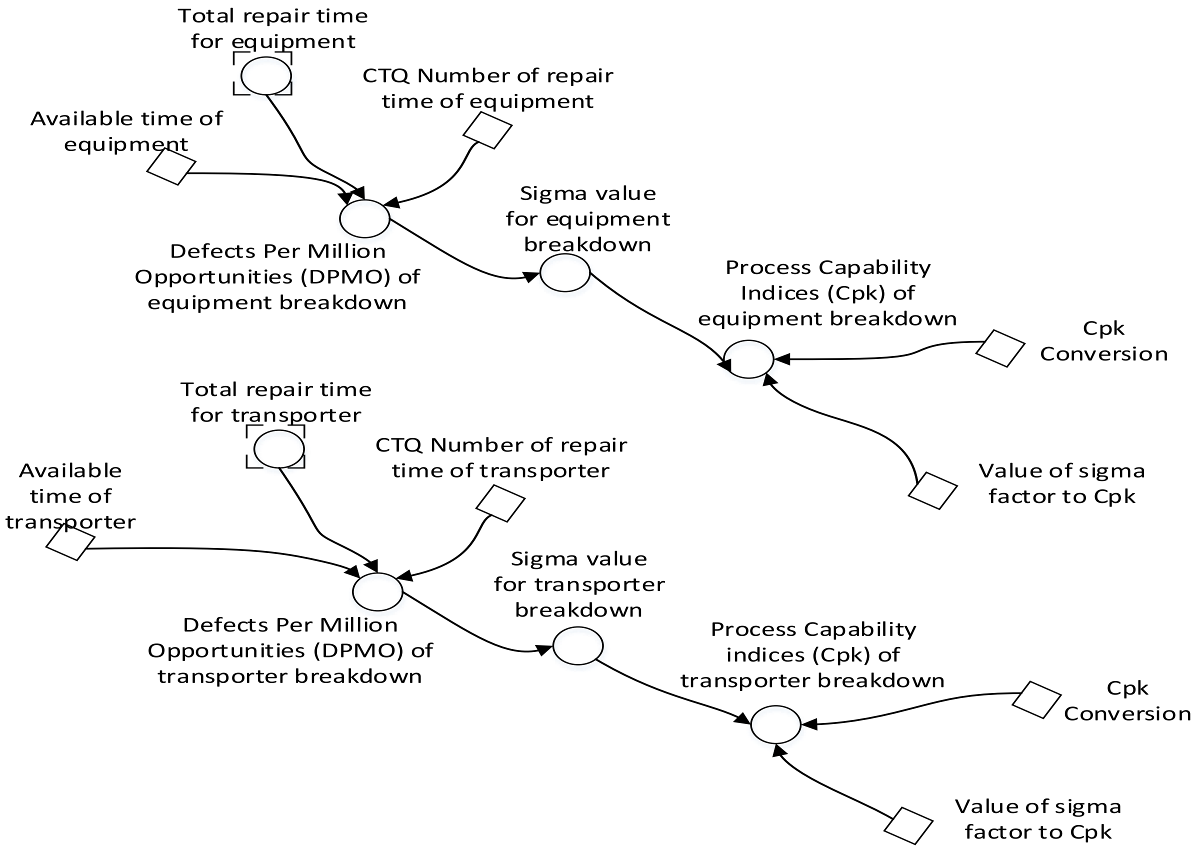


Figure 61. SFD of sigma value and process capability indices of equipment and transporter breakdown

The equipment and transporter breakdown contribute to increasing the repair cost, which is a component of the internal failure cost. The equipment and transporter delay time contributes to increasing the demurrage cost. The SFD of the sigma value and process capability indices of the delay time is depicted in Figure 62:

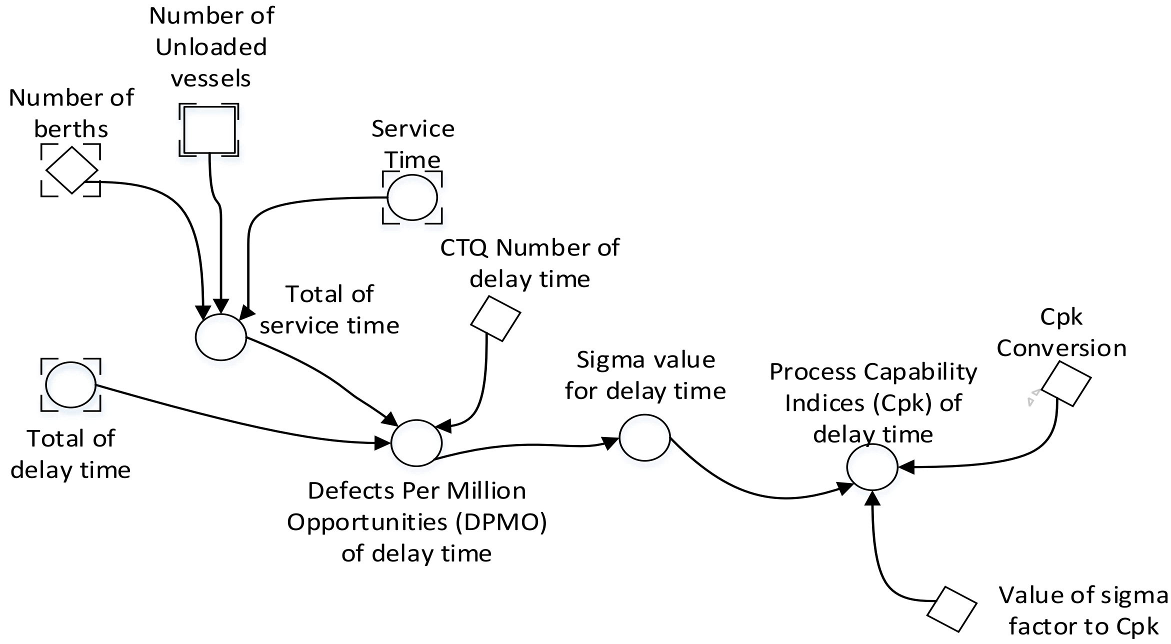


Figure 62. SFD of sigma value and process capability indices of the delay time

5.2 Causal Relationship Between Variables

Several variables have causal relationships according to mathematical functions. The formulation of the mathematical functions is based on the literature, direct observations, and definitions given by experts. The causal relationships come from the auxiliary variables. A causal relationship between the berth occupancy ratio (BOR) and the delay factor arises in the port operation as depicted in Figure 63. According to De Monie (1987), a numerical equation is formulated to determine the correlation between the BOR and the delay factor (df). The input data can be seen in detail in Appendix E with the number of berths being 10. This mathematical equation is determined by data fitting technique that is generated using Matlab© software and a second term of the exponential distribution is chosen with the lowest value of RMSE (root mean squared error). The adjusted R-square (coefficient of determination) of the graph is 0.9994, which means that the correlation between the BOR and the delay factor is fit.

$$\mathrm{df}(\mathrm{t}=\mathrm{i}) = 1.563 \times 10^{-18} \times e^{(43 \times BOR_{(t=i)})} + 0{,}0001014 \times e^{(9.523 \times BOR_{(t=i)})} \quad \mathrm{i} = 0, 1, 2, 3, .., \mathrm{n} \tag{5.1}$$

$$\mathrm{Tw}_{(\mathrm{t}=\mathrm{i})} = \mathrm{Ts}_{(\mathrm{t}=\mathrm{i})} \times \mathrm{df}_{(\mathrm{t}=\mathrm{i})}, \quad \mathrm{i} = 0, 1, 2, 3, .., \mathrm{n} \tag{5.2}$$

where:

df = delay factor,

Tw = the vessel waiting time (day/vessel),

BOR = the berth occupancy ratio,

Ts = the service time.

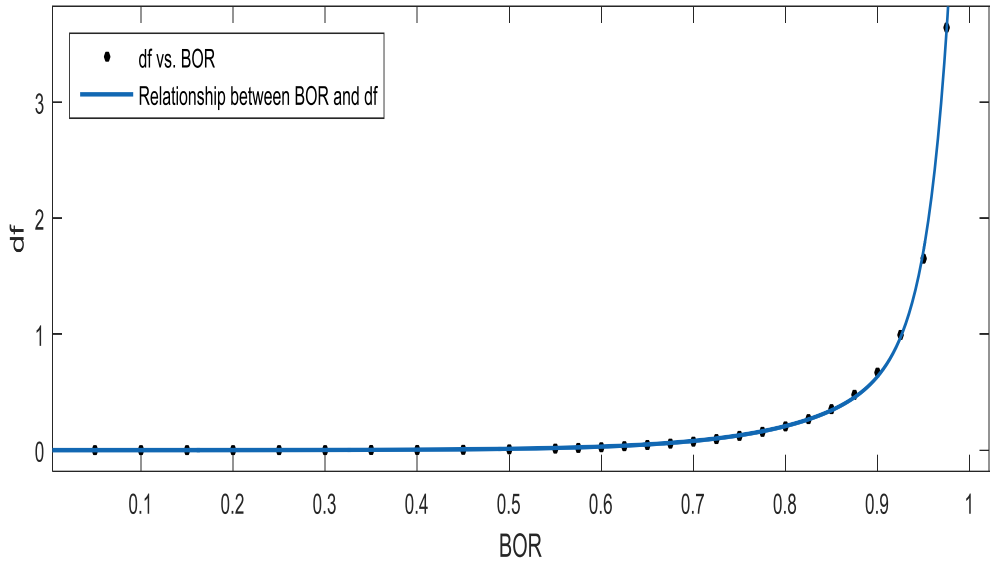


Figure 63.Causal relation between the berth occupancy ratio (BOR) and delay factor (df)

Moreover, causal relationships exist in the port quality level between the cost factors that influence the repair cost, the demurrage cost, the lost cargo cost, and the damaged cargo cost. The source of the following graphs is from experts who defined the causal relationships between these cost factors using 'what-if' analysis based on their experience in the real case. The knowledge elicitation process from experts refers to the method developed by Ford and Sterman (1998), they structured relationships into three steps: the positioning, description, and discussion. These relationships are determined by data fitting techniques that is generated using Matlab© software. The input data can be seen in detail in Appendix E. Georgiadis and Besiou (2008) determined the causal relationship between two variables by expert judgment if historical data were not available. The data pattern that is described by the experts is used to define the following causal relations, with some conversions and adjustments for the stock flow diagram.

1. **Effect of prevention cost on the transporter repair cost**

   The total number of transporter breakdowns should be known in order to calculate the transporter repair cost. The number of transporter breakdowns is obtained based on the experts' (maintenance manager and transport manager of port operation division) definition of the relationship between the percentage of the transporter maintenance cost against the total prevention cost and the number of transporter breakdowns. The graph function is shown in Figure 64 below:

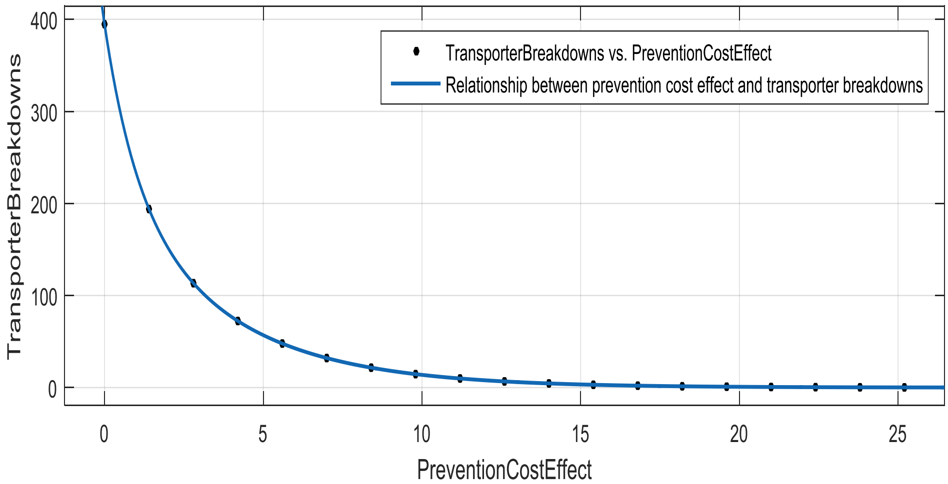


Figure 64. Definition of causal relation between the prevention cost effect and the transporter breakdowns

The graph function in the simulation model is defined based on that curve, which is also defined as the exponential equation. This mathematical equation is determined by data fitting technique that is generated using Matlab© software, as follows:

$$f(x) = 168.3 \times e^{(-1.01\,x)} + 226.4 \times e^{(-0.2798x)} \quad (5.3)$$

2. **Effect of the prevention cost on the equipment repair cost**

   As with the number of transporter breakdowns, the number of equipment breakdowns should be known to calculate the equipment repair cost. The relationship between the prevention cost effect and the number of equipment breakdowns, which is the percentage of equipment maintenance cost per total prevention cost, is also defined by an expert (maintenance manager of port operation division). The graph function is shown in Figure 65 below:

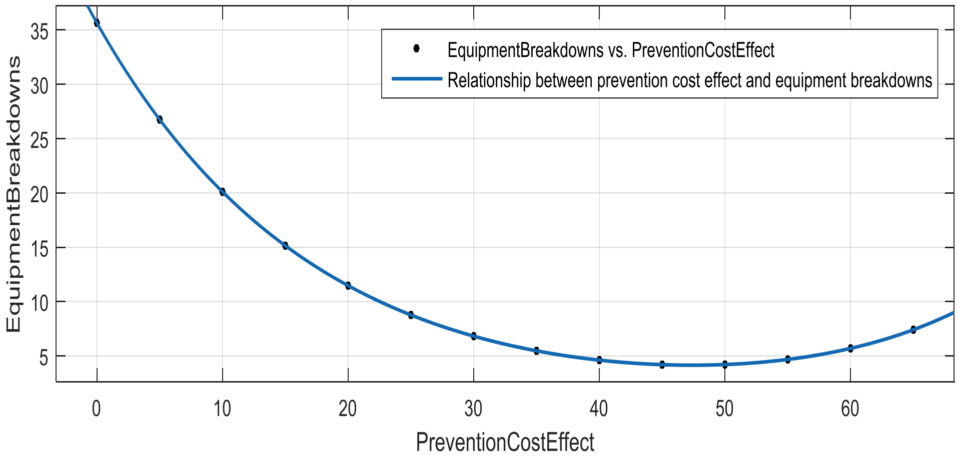


Figure 65. Definition of causal relation between the prevention cost effect and the equipment breakdowns

Based on the graph function above, the relationship follows the exponential equation. The U-shape of this curve shows that there is an over maintenance staff that makes the increasing of the maintenance cost. The increasing of percentage of equipment maintenance cost per total prevention cost is more than 50 %, the number of equipment breakdowns is probably not decrease. Hence, the decision makers should increase percentage of equipment maintenance cost per total prevention cost is less than 50 %. This mathematical equation is determined by data fitting technique that is generated using Matlab© software, as follows:

$$\mathrm{f(x)} = 35.59 \times e^{(-0.05774\,x)} + 0.05956 \times e^{(0.07237x)} \tag{5.4}$$

3. **Effect of the appraisal cost plus prevention cost on the lost cargo cost**

   The percentage of lost cargo should be known to calculate the lost cargo cost. The percentage of lost cargo is obtained from the proportion of the prevention cost effect (70%), which is the safety and security cost per total prevention cost, and the appraisal cost effect (30%) which is the cargo inspection cost per total appraisal cost. The expert definition giving the relationship between the prevention plus appraisal cost and the percentage of lost cargo comes from the logistics services manager of the port operation cargo division. The graph function is shown in Figure 66 below:

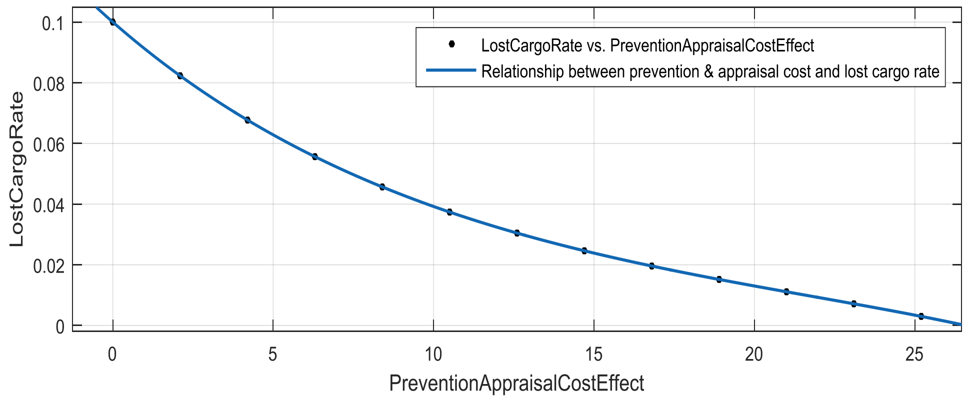


Figure 66. Definition of causal relation between the prevention plus appraisal cost effect and the lost cargo rate

Based on the graph function above, the relationship follows the exponential equation. This mathematical equation is determined by data fitting technique that is generated using Matlab© software, as follows:

$$f(x) = (-8.488\ x\ 10^{-05}) \times e^{(0.1736x)} + 0.1001 \times e^{(-0.09248x)} \qquad (5.5)$$

4. **The appraisal cost plus prevention cost effect to the cargo damaged cost**

The percentage of damaged cargo should be known to calculate the damaged cargo cost. The causal relationship between the percentage of damaged cargo and the appraisal cost plus prevention cost effect is defined by an expert (the logistics services manager of the port operation cargo division). The percentage of damaged cargo is obtained from the proportion of the appraisal cost effect (70%), which is the cargo inspection cost per total appraisal cost, and the prevention cost effect (30%), which is the safety and security cost per total prevention cost. The graph function is presented in Figure 67 below:

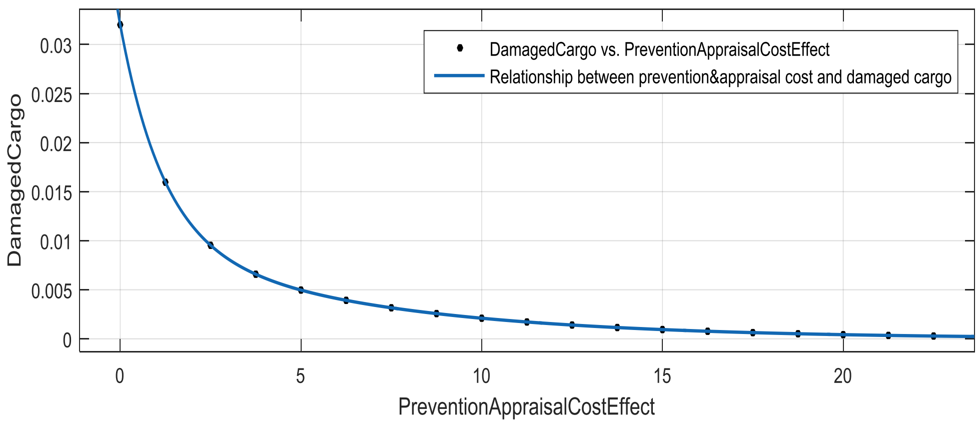


Figure 67. Definition of causal relation between the prevention plus appraisal cost effect and the damaged cargo rate

Based on the graph function above, the relationship follows the exponential equation. This mathematical equation is determined by data fitting technique that is generated using Matlab© software, as follows:

$$\mathrm{f(x)} = 0.02164 \times e^{(-0.8509x)} + 0.01037 \times e^{(-0.1599x)} \tag{5.6}$$

5.3 Mathematical Formulation

The mathematical formulation for all stocks in the stock flow diagram can be expressed in analytical and numerical equations. These formulas are generated partially using Powersim software. The formulas are required to determine exactly the causal relationship between variables. Analytical solution refers to Sterman (2000), to develop the actual functions of the six sigma model. However, the problems cannot be solved using analytical solution because of the complexity of the equations. Therefore, the model will be simulated using numerical approach. Euler integration method is applied to perform the calculation numerically because it is simple and sufficient (Sterman, 2000). The actual functions for analytical solution and the numerical equations are as follows:

1. **Throughput in warehouse (TRwh) and throughput in stockpile yard (TRsy)**

The throughput in the warehouse (TRwh) depends on the delivery rate of cargo to the warehouse ($\mathrm{Or_{wh}}$). Throughput in the warehouse is defined as the accumulation of cargo in the buffer warehouse of the port. The actual function of analytical solution for the throughput in the warehouse (TRwh) is expressed below:

$$\mathrm{TRwh\ (t)} = \mathrm{TRwh_{(t0)}} + \int_{\mathrm{t0}}^{\mathrm{t}} [\mathrm{Or_{wh}(s)}]\mathrm{ds} \tag{5.7}$$

Whereas, the numerical equation for the throughput in the warehouse (TRwh) is expressed below:

$$\mathrm{TRwh_{t\,+\,i*dt}} = \mathrm{TRwh_t} + \mathrm{i} * \mathrm{dt} * \mathrm{Or_{wh(t)}}\ ;\ \mathrm{i} = 0, 1, 2, 3, .., \mathrm{n} \tag{5.8}$$

where dt represents the time interval between periods.

The throughput in the stockpile yard ($\mathrm{TR}sy$) depends on the delivery rate of cargo to the stockpile yard (Or_{sy}). Throughput in the warehouse is defined as the accumulation of cargo in the buffer warehouse of the port. The actual function of analytical solution for the throughput in the stockpile yard ($\mathrm{TR}sy$) is expressed below:

$$\mathrm{TRsy\ (t)} = \mathrm{TRsy_{(t0)}} + \int_{\mathrm{t0}}^{\mathrm{t}} [\mathrm{Or_{sy}(s)}]\mathrm{ds} \tag{5.9}$$

Whereas, the numerical equation for the throughput for the stockpile yard (TRsy) is expressed below:

$$\mathrm{TRsy}_{t+i*dt} = \mathrm{TRsy}_t + i * dt * \mathrm{Or}_{sy(t)};\ i = 0,1,2,3,..,n \tag{5.10}$$

where dt represents the time interval between periods.

2. Number of unloaded vessels (Sv)

The number of unloaded vessels depend on the desired number of unloaded vessels (Svd), the initial number of unloaded vessels ($\mathrm{Sv}_{(t0)}$), and the adjustment time for the arrival rate of vessel (tav). The increasing and decreasing of unloaded vessels is defined as the active vessels in the berths. The actual function of analytical solution for the number of unloaded vessels (Sv) is expressed below:

$$\mathrm{Sv}\,(t) = \mathrm{Sv}_{(t0)} + \int_{t0}^{t} \left[\left(\frac{(\mathrm{Svd}(s) - \mathrm{Sv}(s))}{\mathrm{tav}}\right)\right] ds \tag{5.11}$$

Whereas, the numerical equation for the number of unloaded vessels (Sv) is expressed below:

$$\mathrm{Sv}_{t+i*dt} = \mathrm{Sv}_t + i * dt * \left(\frac{\mathrm{Svd}_t - \mathrm{Sv}_t}{\mathrm{tav}}\right);\ i = 0,1,2,3,..,n \tag{5.12}$$

where dt represents the time interval between periods.

3. Stock in warehouse (Swh) and stock in stockpile yard (Ssy)

The stock in the warehouse depends on the actual number of trucks (Nt), the productivity of a truck (Pt), the delivery rate of cargo to the warehouse (Or_{wh}), and the number of berths (Bn). The actual function of analytical solution for the stock in the warehouse (Swh) is expressed below:

$$\mathrm{Swh}(t) = \mathrm{Swh}_{(t0)} + \int_{t0}^{t} [(\mathrm{Bn} \times \mathrm{Nt}(s) \times \mathrm{Pt}(s) - \mathrm{Or}_{wh}(s))] ds \tag{5.13}$$

Whereas, the numerical equation for the stock in the warehouse (Swh) is expressed below:

$$\mathrm{Swh}_{t+i*dt} = \mathrm{Swh}_t + i * dt * ((\mathrm{Bn} * \mathrm{Nt} * \mathrm{Pt})_t - \mathrm{Or}_{wh(t)});\ i = 0,1,2,3,..,n \tag{5.14}$$

where dt represents the time interval between periods.

The stock in the stockpile yard (Ssy) depends on the speed of the conveyor (Vcy), the productivity of the conveyor (Pcy), and the order rate for the stockpile yard (Or_{sy}). The actual function of analytical solution for the stock in the stockpile yard (Ssy) is expressed below:

$$\mathrm{Ssy(t)} = \mathrm{Ssy}_{(t0)} + \int_{t0}^{t}\left[(\mathrm{Vcy(s)\ x\ Pcy(s)} - \mathrm{Or}_{\ sy}(s))\right]ds \qquad (5.15)$$

Whereas, the numerical equation for the stock in the stockpile yard (Ssy) is expressed below:

$$\mathrm{Ssy}_{t\,+\,i*dt} = \mathrm{Ssy}_t + i * dt * (\mathrm{Vcy}_t * \mathrm{Pcy}_t - \mathrm{Or}_{\ sy(t)});\ i\ =\ 0, 1, 2, 3, .., n \qquad (5.16)$$

where dt represents the time interval between periods.

4. **Number of trucks (Nt), number of cranes (Nc), number of tugboats (Nb), and the conveyor speed (Vcy).**

The number of trucks (Nt) depend on the desired number of trucks (Ntd), the initial number of trucks ($\mathrm{Nt}_{(t0)}$), and the adjustment time for increasing the rate of trucks (tat). The increasing and decreasing of trucks is defined as the active fleets in the berths for delivery process. The actual function of analytical solution for the number of trucks (Nt) is expressed below:

$$\mathrm{Nt\ (t)} = \mathrm{Nt}_{(t0)} + \int_{t0}^{t}\left[\left(\frac{(\mathrm{Ntd(s)} - \mathrm{Nt(s)})}{\mathrm{tat}}\right)\right]ds \qquad (5.17)$$

Whereas, the numerical equation for the number of trucks (Nt) is expressed below:

$$\mathrm{Nt}_{t\,+\,i*dt} = \mathrm{Nt}_t + i * dt * \left(\frac{\mathrm{Ntd}_t - \mathrm{Nt}_t}{\mathrm{tat}}\right);\ i\ =\ 0, 1, 2, 3, .., n \qquad (5.18)$$

where dt represents the time interval between periods.

The number of cranes (Nc)depend on the desired number of cranes (Ncd), the initial number of cranes ($\mathrm{Nc}_{(t0)}$), and the adjustment time for increasing the rate of cranes (tac). The increasing and decreasing of cranes is defined as the active cranes in the berths for loading and unloading process. The actual function of analytical solution for the number of cranes (Nc) is expressed below:

$$\mathrm{Nc\ (t)} = \mathrm{Nc}_{(t0)} + \int_{t0}^{t}\left[\left(\frac{(\mathrm{Ncd(s)} - \mathrm{Nc(s)})}{\mathrm{tac}}\right)\right]ds \qquad (5.19)$$

Whereas, the numerical equation for the number of cranes (Nc) is expressed below:

$$\mathrm{Nc}_{t\,+\,i*dt} = \mathrm{Nc}_t + i * dt * \left(\frac{\mathrm{Ncd}_t - \mathrm{Nc}_t}{\mathrm{tac}}\right);\ i\ =\ 0, 1, 2, 3, .., n \qquad (5.20)$$

where dt represents the time interval between periods.

The number of tugboats (Nb) depend on the desired number of tugboats (Nbd), the initial number of tugboats($Nb_{(t0)}$) and the adjustment time for increasing the rate of tugboats (tab). The increasing and decreasing of tugboats is defined as the active tugboats in the berths for mooring process. The actual function of analytical solution for the number of tugboats (Nb) is expressed below:

$$\mathrm{Nb}\ (\mathrm{t}) = \mathrm{Nb}_{(\mathrm{t0})} + \int_{\mathrm{t0}}^{\mathrm{t}} \left[\left(\frac{(\mathrm{Nbd(s)} - \mathrm{Nb(s)})}{\mathrm{tab}}\right)\right] \mathrm{ds} \tag{5.21}$$

Whereas, the numerical equation for the number of tugboats (Nb) is expressed below:

$$\mathrm{Nb}_{\mathrm{t\,+\,i*dt}} = \mathrm{Nb}_{\mathrm{t}} + \mathrm{i} * \mathrm{dt} * \left(\frac{\mathrm{Nbd}_{\mathrm{t}} - \mathrm{Nb}_{\mathrm{t}}}{\mathrm{tab}}\right);\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.22}$$

where dt represents the time interval between periods.

The conveyor speed (Vcy) depend on the desired conveyor speed (Vcyd), the initial conveyor speed ($Vcy_{(t0)}$), and the adjustment time for increasing the rate of the conveyor speed (ta_{cy}). The increasing and decreasing of conveyor speed is defined as the active conveyor speed in the berths for conveying process. The actual function of analytical solution for the conveyor speed (Vcy) is expressed below:

$$\mathrm{Vcy}\ (\mathrm{t}) = \mathrm{Vcy}_{(\mathrm{t0})} + \int_{\mathrm{t0}}^{\mathrm{t}} \left[\left(\frac{(\mathrm{Vcyd(s)} - \mathrm{Vcy(s)})}{\mathrm{ta}_{\mathrm{cy}}}\right)\right] \mathrm{ds} \tag{5.23}$$

Whereas, the numerical equation for the conveyor speed (Vcy) is expressed below:

$$\mathrm{Vcy}_{\mathrm{t\,+\,i*dt}} = \mathrm{Vcy}_{\mathrm{t}} + \mathrm{i} * \mathrm{dt} * \left(\frac{\mathrm{Vcyd}_{\mathrm{t}} - \mathrm{Vcy}_{\mathrm{t}}}{\mathrm{ta}_{\mathrm{cy}}}\right);\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.24}$$

where dt represents the time interval between periods.

5. **Service time (Ts)**

The service time of vessels (Ts) depends on approach time (AT) and berthing time (BT). The approach time (AT) depends on the operation cycles of tugboat (oct), the capacity of tugboat (ct), and the actual number of tugboats (Nb). Meanwhile, the berthing time (BT) depends on the the the load per vessel (Wv), the lifting capacity of the crane (Lcc), the operation cycles of the crane (Cc), and the actual number of cranes (Nc).

$$\mathrm{AT}_{\mathrm{t=i}} = \frac{1}{\mathrm{oct}_{(\mathrm{t=i})} \times \mathrm{ct}_{(\mathrm{t=i})} \mathrm{x}\ \ \mathrm{Nb}_{(\mathrm{t=i})}};\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.25}$$

$$\mathrm{BT}_{\mathrm{t=i}} = \frac{\mathrm{Wv}_{(\mathrm{t=n})}}{\mathrm{Lcc}_{(\mathrm{t=i})} \times \mathrm{Cc}_{(\mathrm{t=i})} \times \mathrm{Nc}_{(\mathrm{t=i})}};\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.26}$$

$$Ts_{t=i} = \frac{1}{oct_{(t=i)} \times ct_{(t=i)} x\ Nb_{(t=i)}} + \frac{Wv_{(t=n)}}{Lcc_{(t=i)} \times Cc_{(t=i)} \times Nc_{(t=i)}};\ i\ =\ 0, 1, 2, 3, .., n \tag{5.27}$$

6. **Berth occupancy ratio (BOR) and vessel waiting time (Tw)**

The berth occupancy ratio (BOR) is influenced by the number of unloaded vessels (Sv), the service time (Ts), the number of berths (Bn), the number of days in the month (Wd), and the number of working hours per day (Wh). The vessel arrival rate is less than the service time. The berth occupancy ratio (BOR) is expressed below:

$$BOR_{t=i} = \frac{Sv_{(t=i)} \times Ts_{(t=i)}}{Bn_{(t=i)} \times Wd_{(t=i)} \times Wh_{(t=i)}};\ i\ =\ 0, 1, 2, 3, .., n \tag{5.28}$$

The vessel waiting time (Tw) is influenced by the service time (Ts) and a delay factor (df) that relates to the BOR as follows:

$$Tw_{t=i} = Ts_{t=i} \times\ df_{(t=i)}\ ; i = 0, 1, 2, 3, .., n \tag{5.29}$$

$$df_{t=i} = 1.563 \times 10^{-18} \times e^{(43 \times BOR_{(t=i)})} + 0.0001014 \times e^{(9.523 \times BOR_{(t=i)})}; i = 0, 1, 2, 3, .., n \tag{5.30}$$

The relationship between the BOR and the delay factor is determined by the second term exponential based on Monie (1987) with the adjusted R-squared value of 0.9994. This relationship is determined by data fitting technique that is generated using Matlab© software.

7. **Cost of Poor Quality (COPQ)**

The cost value of poor quality is obtained from the accumulation of conformance cost, non-conformance cost, and opportunity cost. The actual function of analytical solution for the cost of poor quality ($COPQ$) is expressed below:

$$COPQ\ (t) = COPQ_{(t0)} + \int_{t0}^{t} \left[\left(\frac{(CC+NCC+OC)(s)}{ta_{co}}\right)\right] ds \tag{5.31}$$

Whereas, the numerical equation for the cost of poor quality ($COPQ$) is expressed below:

$$COPQ_{t\ +\ i*dt} = COPQ_{t} + i * dt * \left(\frac{(CC+NCC+OC)_{t}}{ta_{co}}\right);\ i\ =\ 0, 1, 2, 3, .., n \tag{5.32}$$

where $COPQ$ represents the cost of poor quality (US$), CC is the conformance cost (US$), NCC is the non-conformance cost (US$), and OC represents the opportunity cost (US$), ta_{co} is the adjustment time for the COPQ rate (month), and dt represents the time interval between periods.

8. **Conformance cost (CC)**

The inflow of the conformance cost comes from the rate of the total prevention cost and appraisal cost, so the cost factors that have the major effect on the conformance cost are the prevention cost and appraisal cost. The actual function of analytical solution for the conformance cost (CC) is expressed below:

$$\mathrm{CC}\ (\mathrm{t}) = \mathrm{CC}_{(\mathrm{t0})} + \int_{\mathrm{t0}}^{\mathrm{t}} \left[\left(\frac{(\mathrm{PC+AC})(\mathrm{s})}{\mathrm{ta_{cc}}}\right)\right] \mathrm{ds} \tag{5.33}$$

Whereas, the numerical equation for the conformance cost (CC) is expressed below:

$$\mathrm{CC}_{\mathrm{t\,+\,i*dt}} = \mathrm{CC_t} + \mathrm{i} * \mathrm{dt} * \left(\frac{(\mathrm{PC+AC})_{\mathrm{t}}}{\mathrm{ta_{cc}}}\right);\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.34}$$

where CC represents the conformance cost (US$), PC represents the prevention cost (US$), AC represents the appraisal cost (US$), $\mathrm{ta_{cc}}$ is the adjustment time for the conformance cost rate (month), and dt represents the time interval between periods. The actual function of analytical solution for the prevention cost (PC) is expressed below:

$$\mathrm{PC}\ (\mathrm{t}) = \mathrm{PC}_{(\mathrm{t0})} + \int_{\mathrm{t0}}^{\mathrm{t}} \left[\left(\frac{(\mathrm{QEC+MRC+SSC+PMC+RTC+WTC})(\mathrm{s})}{\mathrm{ta_{pc}}}\right)\right] \mathrm{ds} \tag{5.35}$$

Whereas, the numerical equation for the prevention cost (PC) is expressed below:

$$\mathrm{PC}_{\mathrm{t\,+\,i*dt}} = \mathrm{PC_t} + \mathrm{i} * \mathrm{dt} * \left(\frac{(\mathrm{QEC+MRC+SSC+PMC+RTC+WTC})_{\mathrm{t}}}{\mathrm{ta_{pc}}}\right);\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.36}$$

Where:

QEC = the quality engineering cost (US$),

MRC = the marketing research cost (US$),

SSC = the safety and security cost (US$),

PMC = the preventive maintenance cost (US$),

RTC = the recruiting cost (US$),

WTC = the worker training cost (US$),

$\mathrm{ta_{pc}}$ = the adjustment time for the prevention cost rate (month),

dt = the time interval between periods.

The analytical solution for the appraisal cost (AC) is expressed below:

$$\mathrm{AC}\ (\mathrm{t}) = \mathrm{AC}_{(\mathrm{t0})} + \int_{\mathrm{t0}}^{\mathrm{t}} \left[\left(\frac{(\mathrm{TCC+ECC+CIC+DSC+QAC+CCC})(\mathrm{s})}{\mathrm{ta_{ac}}}\right)\right] \mathrm{ds} \tag{5.37}$$

Whereas, the numerical equation for the appraisal cost (AC) is expressed below:

$$\mathrm{AC}_{t + i*dt} = \mathrm{AC}_t + i * dt * \left(\frac{(\mathrm{TCC+ECC+CIC+DSC+QAC+CCC})_t}{\mathrm{ta_{ac}}}\right);\ i\ =\ 0, 1, 2, 3, .., n \qquad (5.38)$$

where:

AC = the appraisal cost (US$),

TCC = the transporter checking cost (US$),

ECC = the equipment checking cost (US$),

CIC = the cargo inspection cost (US$),

DSC = the draft survey cost (US$),

QAC = the quality audit cost (US$),

CCC = the custom clearance cost (US$),

$\mathrm{ta_{ac}}$ = the adjustment time for the appraisal cost rate (month),

dt = the time interval between periods.

9. Non-conformance cost (NCC)

This cost component comprises the internal failure cost and external failure cost. The actual function of analytical solution for the non-conformance cost (NCC) is expressed below:

$$\mathrm{NCC}\ (t) = \mathrm{NCC}_{(t0)} + \int_{t0}^{t} \left[\left(\frac{(\mathrm{IFC+EFC})(s)}{\mathrm{ta_{nc}}}\right)\right] ds \qquad (5.39)$$

Whereas, the numerical equation for the non-conformance cost (NCC) is expressed below:

$$\mathrm{NCC}_{t + i*dt} = \mathrm{NCC}_t + i * dt * \left(\frac{(\mathrm{IFC+EFC})_t}{\mathrm{ta_{nc}}}\right);\ i\ =\ 0, 1, 2, 3, .., n \qquad (5.40)$$

where NCC represents the non-conformance cost (US$), IFC represents the internal failure cost (US$), EFC represents the external failure cost (US$), $\mathrm{ta_{nc}}$ represents the adjustment time for the non-conformance cost rate (month), and dt represents the time interval between periods. The actual function of analytical solution for the internal failure cost (IFC) is expressed below:

$$\mathrm{IFC}(t) = \mathrm{IFC}_{(t0)} + \int_{t0}^{t} \left[\left(\frac{(\mathrm{CDC+DC+LCC+RC})(s)}{\mathrm{ta_{ic}}}\right)\right] ds \qquad (5.41)$$

Whereas, the numerical equation for the internal failure cost (IFC) is expressed below:

$$\mathrm{IFC}_{t + i*dt} = \mathrm{IFC}_t + i * dt * \left(\frac{(\mathrm{CDC+DC+LCC+RC})_t}{\mathrm{ta_{ic}}}\right);\ i\ =\ 0, 1, 2, 3, .., n \qquad (5.42)$$

where IFC represents the internal failure cost (US$), CDC represents the damaged cargo cost (US$), DC represents the demurrage cost (US$), LCC represents the lost cargo cost (US$), RC represents the repair cost (US$), $\mathrm{ta_{ic}}$ represents the adjustment time for the internal failure cost rate (month), and dt represents the time interval between periods. The actual function of analytical solution for the external failure cost (EFC) is expressed below:

$$\mathrm{EFC(t)} = \mathrm{EFC_{(t0)}} + \int_{t0}^{t} \left[\left(\frac{\mathrm{(DDC+CAC)(s)}}{\mathrm{ta_{ec}}}\right)\right] \mathrm{ds} \tag{5.43}$$

Whereas, the numerical equation for the external failure cost (EFC) is expressed below:

$$\mathrm{EFC_{t\,+\,i*dt}} = \mathrm{EFC_t} + \mathrm{i} * \mathrm{dt} * \left(\frac{\mathrm{(DDC+CAC)_t}}{\mathrm{ta_{ec}}}\right);\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.44}$$

where EFC represents the external failure cost (US$), DCC represents the discount due to damaged cost (US$), CAC represents the complaint adjustment cost (US$), $\mathrm{ta_{ec}}$ represents the adjustment time for the external failure cost rate (month), and dt represents the time interval between periods.

10. Opportunity cost (OC)

The opportunity cost is calculated from the total unavailable worker compensation cost, cargo compensation cost, and unavailable transporter and equipment cost. The actual function of analytical solution for the opportunity cost (OC) is expressed below:

$$\mathrm{OC(t)} = \mathrm{OC_{(t0)}} + \int_{t0}^{t} \left[\left(\frac{\mathrm{(UWCC+CRGC+UTECC)(s)}}{\mathrm{ta_{oc}}}\right)\right] \mathrm{ds} \tag{5.45}$$

Whereas, the numerical equation for the opportunity cost (OC) is expressed below:

$$\mathrm{OC_{t\,+\,i*dt}} = \mathrm{OC_t} + \mathrm{i} * \mathrm{dt} * \left(\frac{\mathrm{(UWCC+CRGC+UTECC)_t}}{\mathrm{ta_{oc}}}\right);\ \mathrm{i}\ =\ 0, 1, 2, 3, .., \mathrm{n} \tag{5.46}$$

where OC represents the opportunity cost (US$), UWCC represents the unavailable worker compensation cost (US$), CRGC represents the cargo compensation cost (US$), UTECC represents the unavailable transporter and equipment cost (US$), $\mathrm{ta_{oc}}$ represents the adjustment time for the opportunity cost rate (month), and dt represents the time interval between periods.

11. Sigma value (SV)

The sigma value is calculated based on continuous and discrete data. The formulation is as follows:

$$\mathrm{SV} = \mathrm{Norminv}\left[\frac{1{,}000{,}000 - \mathrm{DPMO}}{1{,}000{,}000}\right] + 1.5 \tag{5.47}$$

For continuous data,

$$\mathrm{DPMO} = \left[(1 - \mathrm{P}(\mathrm{Z} < \left(\frac{\mathrm{USL} - \bar{\mathrm{X}}}{\sigma}\right) + \mathrm{P}(\mathrm{Z} < \left(\frac{\mathrm{LSL} - \bar{\mathrm{X}}}{\sigma}\right)\right] \mathrm{x}\ 1{,}000{,}000 \tag{5.48}$$

$$\sigma = \sqrt{\frac{\sum_{\mathrm{i}}^{\mathrm{n}} (\mathrm{Xi} - \bar{\mathrm{X}})^2}{\mathrm{n} - 1}} \tag{5.49}$$

$$\bar{\mathrm{X}} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{Xi}}{\mathrm{n}} \tag{5.50}$$

Whereas, for discrete data,

$$\mathrm{DPMO} = \frac{\bar{\mathrm{u}}}{\sum \mathrm{CTQ}}\ \mathrm{x}\ 1{,}000{,}000 \tag{5.51}$$

$$\bar{\mathrm{u}} = \frac{\sum_{\mathrm{j}=1}^{\mathrm{n}} \mathrm{defect}_{\mathrm{j}}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{unit}_{\mathrm{i}}} \tag{5.52}$$

where DPMO represents defects per million opportunities, σ represents natural tolerance, $\bar{X}$ represents the sample average, CTQ represents critical to quality, and $\bar{u}$ represents the sample average for discrete data.

12. Process capability indices (Cpk)

The process capability indices with the calculation Cpk. The formulation is as follows:

For continuous data,

$$\mathrm{Cpk} = \min : [\mathrm{CpU}, \mathrm{CpL}] \tag{5.53}$$

$$\mathrm{Cpk} = \min : \left[\frac{\bar{X} - LSL}{3\sigma}, \frac{USL - \bar{X}}{3\sigma}\right] \tag{5.54}$$

$$\sigma = \sqrt{\frac{\sum_{\mathrm{i}}^{\mathrm{n}} (\mathrm{Xi} - \bar{\mathrm{X}})^2}{\mathrm{n} - 1}} \tag{5.55}$$

$$\bar{\mathrm{X}} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{Xi}}{\mathrm{n}} \tag{5.56}$$

Whereas, for discrete data,

$$\mathrm{Cpk} = \frac{\text{Sigma Value}}{3} \tag{5.57}$$

where CpU represents the process capability indices (upper), CpL represents the process capability indices (lower), σ represents a natural tolerance, $\mathrm{U}SL$ represents the upper specification limit, $\mathrm{L}SL$ represents the lower specification limit, and $\bar{X}$ represents the sample average.

Chapter 6

Empirical Analysis

6.1 Description of the Case Study

The model of six sigma in ports is proved in the real case by the validation process. Also, real data in a port are required to run the base case simulation. This model is checked by actual data to determine whether it fits or not with the real case. A port is required to become a case study so the model validation can be proved. Data have been taken on the CDG Port located in Banten, Indonesia. The model of the port operation has been validated by data from the port operation derived from the vessel report for 2013. The 2013 vessel report can be seen in detail in Appendix C. The data include the number of vessels, cargo throughput, average load per vessel, service time, berth occupancy ratio, and vessel waiting time. Meanwhile, a model of the port's quality level has been validated by data on the cost of poor quality in 2013, and detailed data on the cost of poor quality can also be seen in Appendix C. These data include the internal failure cost, external failure cost, non-conformance cost, appraisal cost, prevention cost, conformance cost, opportunity cost, and cost of poor quality.

The port quality level depends on the poor quality that arises from failure activities. Eliminating waste can improve the port performance indicator. Mwasenga (2012) stated that ports must develop an appropriate tool to evaluate and improve the port performance indicators, which include the service and utilization indicators. The service indicators involve the operation time and availability of infrastructures, while the utilization indicators consist of the berth occupancy and the storage utilization. This research focuses on reducing the vessel waiting time with the berth occupancy ratio (BOR) value as an indicator. The relationship between the BOR and the vessel waiting time follows the exponential distribution referring to Monie (1987). The vessel waiting time relates to the operation time as one of the service indicators. Meanwhile, berth occupancy ratio is one of the utilization indicators. Therefore, reducing the vessel waiting time obviously is part of a trade-off due to the BOR value as an indicator of the berth utilization. According to Alderton (2008), the priority of the port manager is to minimize the time in port, which will increase the capital and growth of the vessels, and thus improve the customer competition. Failure activities in the port operation can reduce the quality level of the port. Poor quality port operation can cause internal failure costs, thus reducing the port performance. In this research, internal failure costs such as the demurrage cost, repair cost, lost cargo cost, and damaged cargo cost are utilized to measure the quality level at the port.

6.2 Overview CDG Port at Banten, Indonesia

6.2.1 Profile of CDG Port

CDG Port is one of the biggest ports in Indonesia and provides loading and unloading facilities for all raw materials, products, and spare parts. In 1970, it started to build the first pellets dock with a length of 300 meters and the apron area of 33 meters. This dock was built to accommodate vessels of 50,000 DWT. Construction of 270 meters of the sponge iron docks was followed by the completion of the pellets dock. This dock serves vessels of 50,000 DWT. A factory bar mill started production in the same period. A dock for barges was completed in 1984, and in 1990 an additional pellets dock was constructed by expanding an existing dock to an additional 285 meters with a 25.2 meters wide apron. This latest dock was completed in 1992, and is able to accommodate vessels of 70,000 DWT. In February 1995, the construction of a dock for scrap steel was started. In 1997, the dock was completed with a length of 240 meters.

CDG Port has a specialization operating as a port terminal for dry bulk cargos. CDG Port gives a total solution to handle bulk materials. The aim of dry bulk port terminals is to store the bulk materials temporarily for their customers. Also, there are stockpiles and warehouses at the dry bulk port terminals that act as a buffer to avoid delays in the shipment to end customers. Numerous facilities are managed by CDG Port, such as the dock, dealing with equipment, supporting equipment, supporting facilities, warehouses, and safety and security. Services offered by CDG Port are loading and unloading services, logistics services, mooring services, supporting services, and loading and unloading service tools. Also CDG port handles piloting, stevedoring services, storage services and an industry area handling materials such as corn, soybean, raw sugar, iron ore pellet, coal, gypsum, general cargo and scrap iron. In addition, CDG Port also handles other potential cargoes such as fertilizer, salt, wheat, fresh fruit hydrocarbon oil, silica sand and many more. Dynamic activities in business, industry and investment are becoming more convenient in the integrated port and industrial estate of CDG. The area where CDG Port runs the operation affects the efficiency and the practicality of import and export activities.

CDG Port, which is also well known as the deepest port in Indonesia with a depth of up to 21 m LWS (low water spring tide), is located in the Sunda Strait in Banten, West Java, Indonesia. So, many big or super capesize vessels (± 200,000 DWT or dead weight tonnage) can be moored in the dock or berths of the port. The port is managed by a company that runs the business and operations throughout the port with several facilities:

1. Docks or berths

The berths owned by the company are located in two terminals, namely Terminal 1 with 12 berths and Terminal 2 with 2 berths. Each berths allocated to its company partner to achieve the best loading and unloading process. Fourteen berths which can be berthed various type of vessel from barge, handysize, handymax, panamax until super capesize vessel up to 200,000 DWT.

2. **Handling equipment**

   The company equipment supports the handling process in the port, with the following facilities:

   a. Four units of ship unloader crane with capacities of 750 tons per hour (TPH) and safe working loads (SWL) of 20 tons
   b. Two units of portal harbor crane (PHC) with capacities of 750 TPH and safe working loads (SWL) of 100 tons
   c. One multipurpose crane (MPC) with a capacity of 1,500 TPH and safe working load (SWL) of 40 tons
   d. Three conveyor lines that consist of two 7 km lines that connect docks in Terminal 1 with the stock yard that is available with design capacities of 1,500 TPH and one 1.6 km conveyor line in Terminal 2 with design capacities of 3,000 TPH
   e. Two units of gantry grab ship unloader (GGSU) crane with capacities of 1,500 TPH and safe working load (SWL) of 45 tons
   f. Truck feeding hopper with a capacity of 2,000 TPH, consists of 4 hoppers, that are also connected to the warehouse or the available storage of the company partners.

3. **Warehouse**

   There are ten units of adjacent stores with a total area of 53,800 m^2 that can hold over 210,000 tons; these are also used as a place to keep bulk dry goods and for open storage with a total area of 250,000 m^2 for holding pipes, coal, salt, and other unloaded goods.

4. **Supporting facilities and equipment**

   This port also provides supporting facilities and equipment like a workshop, bagging machine, 50 tons dump trucks, trailers, hopper trucks, loaders, excavators, forklifts, scales, easy access to toll and railway, etc.

The location of CDG Port Terminal 1 with several facilities can be seen in Figure 68 below:

Figure 68. Terminal 1 of CDG Port with several facilities (CDG Port, 2014)

Whereas Terminal 2 of CDG Port can be seen in Figure 69 below:

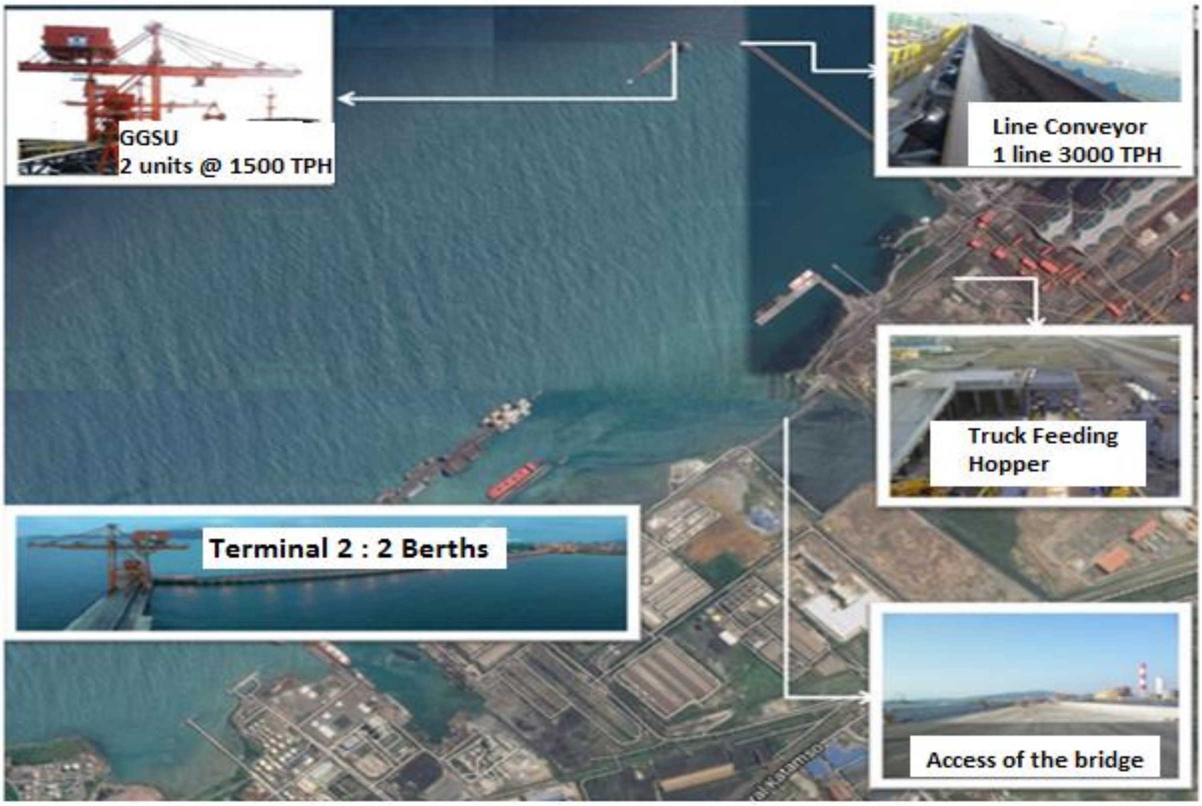


Figure 69. Terminal 2 of CDG Port with several facilities (CDG Port, 2014)

Each year, this port company loads and unloads approximately 8.5 million tons of bulk goods including iron ore pellets, coals, gypsum pellets, iron scrap, corn, fertilizer, raw sugar, and so on. Besides loading and unloading activities, the company also provides additional services such as a mooring service, loading and unloading of heavy equipment, a stevedoring service, logistics service, and piloting. Details of the average discharging rate are shown in Table 3 below:

Table 3.Discharging rate in CDG Port (CDG Port, 2014)

Type of cargo	Discharging rate (ton/day)
Iron Ore Pallets	27,000
Corals	10,000
Corn	10,000
Soybean	10,000
Soybean Meal	6,000
Gypsum	6,000
Salt	5,000
Sugar	5,000

6.2.2 Lean Supply Chain in CDG Port

Alderton (2008) adds that many ports take advantage of their strategic position in the chain of logistics by the value-added services they can offer in their strategic location. The port's competitiveness requires not only good infrastructure but also the right management of port operations. According to Yeo et al.(2008), a port's competitiveness attributes include port service, hinterland condition, availability, convenience, logistics cost, regional centre and connectivity. The lean supply chain in a port adopts lean concepts in managing the elimination of waste in the entire supply chain. With the lean in the supply chain, the port's performance can be increased. Marlow and Casaca (2003) measured the performance at an intra-port level by comparing the actual throughput and the optimum port. The opportunity of lean in the supply chain at ports enables them to deliver cargo quickly and provide a service in line with the market demand while eliminating waste in their processes.

This research employs the quality at the source as one of the advanced lean tools to eliminate or reduce the sources of waste. The quality at the source is one element of Total Quality Management (TQM) that contains a concept and principle by involving all members of the organization in improving the quality. Cheng and Choy (2007) state that the top management's commitment and participation are a significant success factor in quality management in the shipping industry. The commitment and participation of management are the main principles of TQM. This research uses the six sigma methodology as one of the TQM methods to improve quality in ports. The six sigma methodology focuses on eliminating poor quality in port operation activities. According to Hu and Lee (2011), the quality service of ports is the main factor that influences the customer's choice of port. They add that the attributes of quality that influence dissatisfaction with ports are: congestion; inappropriate resolution of accident claims; lack of a monitoring system in port services; poor transparency in the negotiation of prices and the administrative process; and a poor level of service of cargo claims and the user's need for ports. Santoso et al. (2015) generated the optimal number of trucks for the loading and unloading process in CDG Port and established scenarios to reduce truck congestion. The transporter or equipment delay time is one area of waste in a port that influences customer satisfaction.

Based on the six sigma model to improve the lean supply chain in ports, the waste in CDG Port arises in the internal failure activities. These activities cause poor quality, equipment and transporter delays, equipment and transporter breakdowns, lost cargo, and damaged cargo. These wastes in CDG Port are also influenced by other activities. Control activities such as prevention and appraisal activity influence the internal failure activity; for example, the preventive maintenance of equipment and transporters affects the equipment and transporter breakdown. Besides, the internal failure activities cause internal failure costs, which are the cost of poor quality elements that should be eliminated or reduced.

6.3 The Base Case of Simulation

Simulations for the base case were executed by using historical data from 2013. The input data can be seen in detail in Appendix C. Furthermore, all constants, functions, and equations in model simulations can be seen in detail in Appendix D.

6.3.1 Limitations and assumptions

Some limitations and assumptions are needed to run the base case simulation, as follows:

a. This model was input with real data on the dry bulk port from CDG Port Terminal 1 in the year 2013.
b. Powersim Software Studio 10 Academic User was utilized to carry out the simulation.
c. The relationship between variables and checking of data distribution were calculated statistically by other software such as Matlab, Statfit, and Minitab.
d. Demand for unloading cargo in the port is continuous.
e. The equipment and transporter capacity is based on actual conditions in the port.
f. Operational costs in the port are beyond the scope of this research.

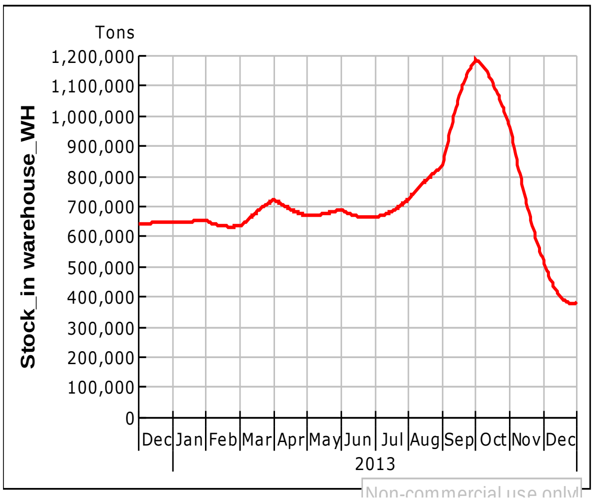
6.3.2 Simulation results for the base case

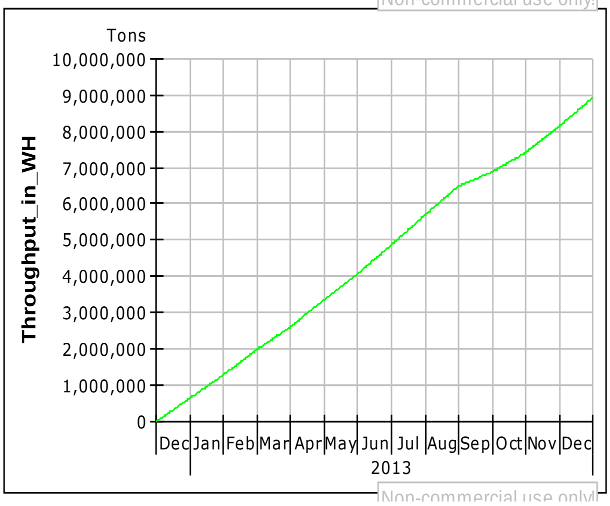
This simulation determined values such as the cumulative throughput in the warehouse (fertilizer, corn, sugar, etc.) and the cumulative throughput in the stockpile yard (iron ore). Also, the simulation established the number of unloaded vessels, the vessel service and waiting time, and the value of the berth occupancy ratio (BOR).

Regarding the simulation result described in Table 4, the stock in the warehouse increased markedly at the beginning of September 2013 and then decreased extremely at the beginning of October. This was because the delivery rate of cargo. In September 2013, the delivery rate of the cargo was low so that the unloaded goods accumulated in the warehouse. The value of stock in the warehouse reached the highest value at 1,185,093.74 tons at the beginning of October 2013. The port terminal received a total throughput of 8,141,277 tons for the warehouse in December 2013. The behavior of the stock in the warehouse is oscillation because the state of system is seeking to reach an equilibrium condition. The stock in the warehouse characterizes the state of the inventory system in the port and become a variable for improvements.

Table 4. Simulation result of stock and throughput in warehouse (WH)

Time	Stock_in warehouse_WH (Tons)	Delivery_rate_of cargo_in_WH (Tons/mo)	Throughput_in_WH (Tons)
Jan 01, 2013	648,000.00	643,393.00	643,393.00
Feb 01, 2013	652,607.00	697,657.00	1,286,786.00
Mar 01, 2013	635,391.01	627,443.00	1,984,443.00
Apr 01, 2013	722,454.04	749,638.00	2,611,886.00
May 01, 2013	668,397.55	710,307.00	3,361,524.00
Jun 01, 2013	689,496.29	803,358.00	4,071,831.00
Jul 01, 2013	666,388.64	822,368.00	4,875,189.00
Aug 01, 2013	725,003.38	800,920.00	5,697,557.00
Sep 01, 2013	834,891.37	381,197.00	6,498,477.00
Oct 01, 2013	1,185,093.74	534,782.00	6,879,674.00
Nov 01, 2013	962,060.25	726,821.00	7,414,456.00
Dec 01, 2013	521,685.83	787,802.00	8,141,277.00

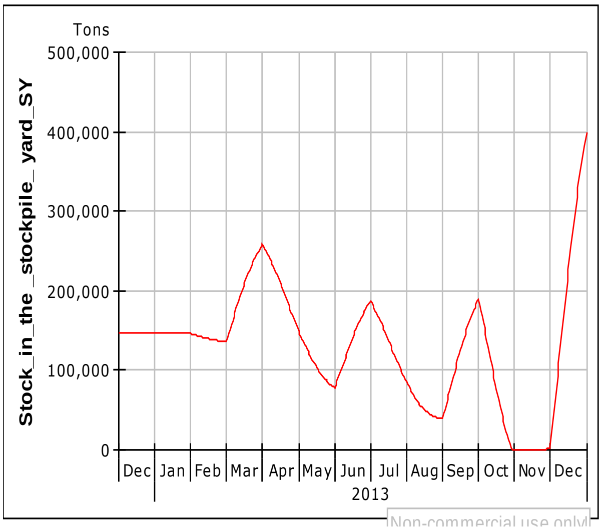




The stock in the stockpile yard decreased at the beginning of April 2013 until October 2013. The throughput in the stockpile yard increased gradually. The throughput of the stockpile yard was affected by the delivery rate to the yard. The delivery rate in a particular period affects the operational processes in the port terminal. The port terminal received a total throughput of 1,699,855.60 tons for the stockpile yard in December 2013 as seen in Table 5:

Table 5. Simulation result of stock and throughput in stockpile yard (SY)

Time	Stock_in_the _stockpile_ yard_SY (Tons)	Delivery_rate_of_ cargo_in SY (Tons/s²)	Throughput_in_SY (Tons)
Jan 01, 2013	145,952.00	6.52e-7	145,952.00
Feb 01, 2013	145,952.00	7.15e-7	291,904.00
Mar 01, 2013	136,114.10	0.00	452,001.00
Apr 01, 2013	258,503.92	7.07e-7	452,001.00
May 01, 2013	149,278.96	6.68e-7	610,271.00
Jun 01, 2013	77,841.36	0.00	759,961.00
Jul 01, 2013	187,100.46	7.01e-7	759,961.00
Aug 01, 2013	85,256.96	7.20e-7	916,908.00
Sep 01, 2013	39,915.96	0.00	1,078,216.00
Oct 01, 2013	189,434.57	1.40e-6	1,078,216.00
Nov 01, 2013	0.00	8.94e-7	1,381,578.61
Dec 01, 2013	3,920.38	8.01e-8	1,699,855.60



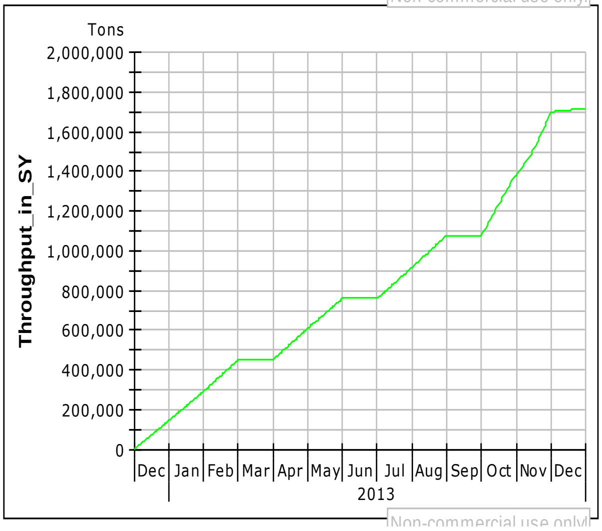
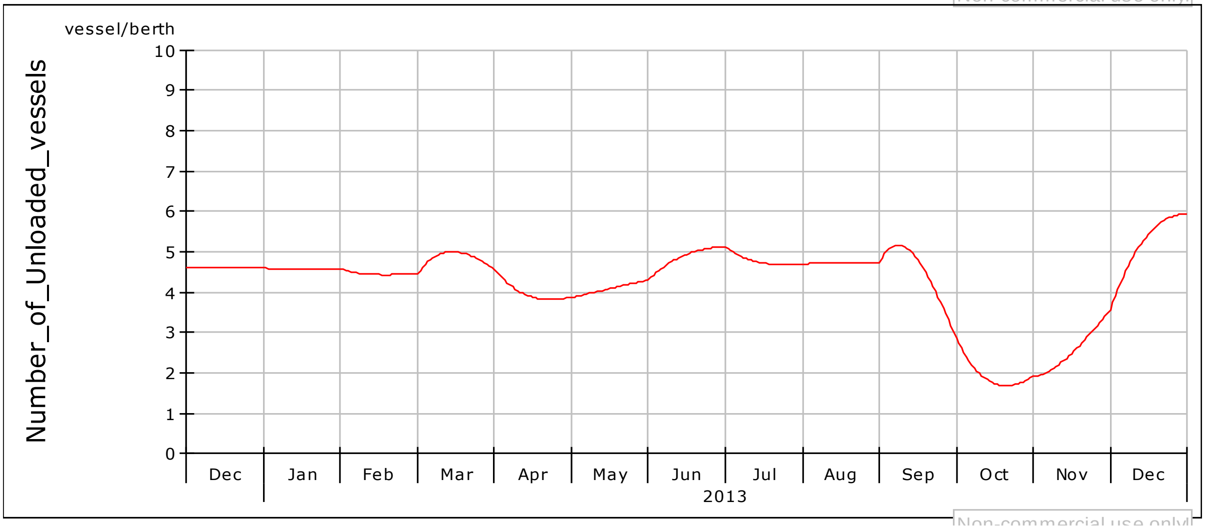


Table 6 shows that the delivery rate per month is also affected by the number of unloaded vessels, which oscillated in 2013. The port terminal received the highest number of unloaded vessels at 5.12 vessels per berth in July 2013, with an average of 21,289 tons of load per vessel. Also, the behavior of the stock in the stockpile yard is oscillation because the state of system is seeking to reach an equilibrium condition. This condition occurs because there is a discrepancy or different between the stock in the stockpile yard and the desired stock in the stockpile yard.

Table 6. Simulation result of the number of unloaded vessels

Time	Load_of_vessel (Tons/(mo*vessel))	Number_of_Unloaded_vessels (First) (vessel/berth)
Jan 13	17,160.00	4.59
Feb 13	19,494.00	4.57
Mar 13	12,805.00	4.47
Apr 13	19,737.00	4.58
May 13	20,000.00	3.88
Jun 13	15,158.00	4.30
Jul 13	21,289.00	5.12
Aug 13	21,869.00	4.70
Sep 13	12,297.00	4.72
Oct 13	17,679.00	2.88
Nov 13	25,103.00	1.91
Dec 13	16,115.00	3.56

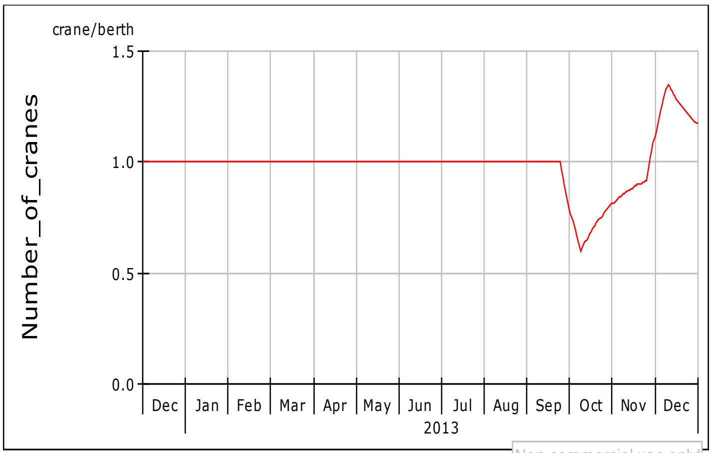


Moreover, the rate of delivery orders per month also affected the strategy on operating equipment in the port terminal. The machines were operated depending on the desired outputs. The equipment operations are shown in Table 7 below. In 2013, the port terminal was expected to have at least two cranes per berth, nine trucks per berth and one tugboat per berth. Furthermore, the conveyor was expected to be able to operate at a speed of at least 0.02 m/s. In October 2013, the equipment operations started to decrease gradually, meaning that the equipment was not operating at maximum capacity. The lowest point was in November 2013, when the order rate and the vessel numbers in November were the least, and needed to be unloaded but at an increased service time.

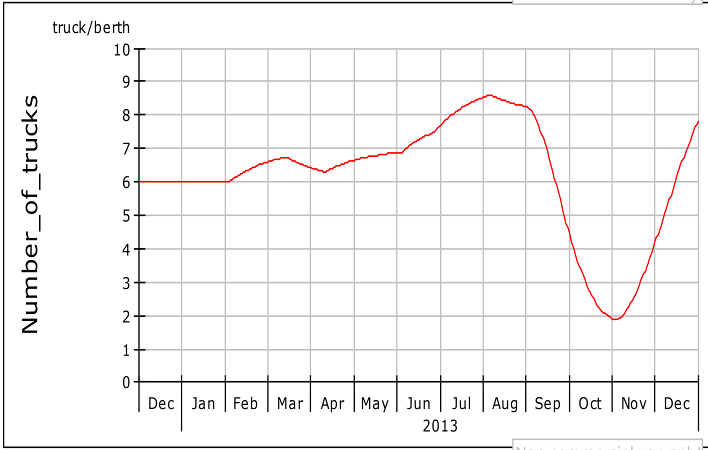
Also, the behavior of the equipment operations is oscillation because the state of system is seeking to reach an equilibrium condition. All equipment are made to reach an equilibrium condition because this research uses the pull system approach based on the customer order rate.

Table 7. Simulation result of equipment operations

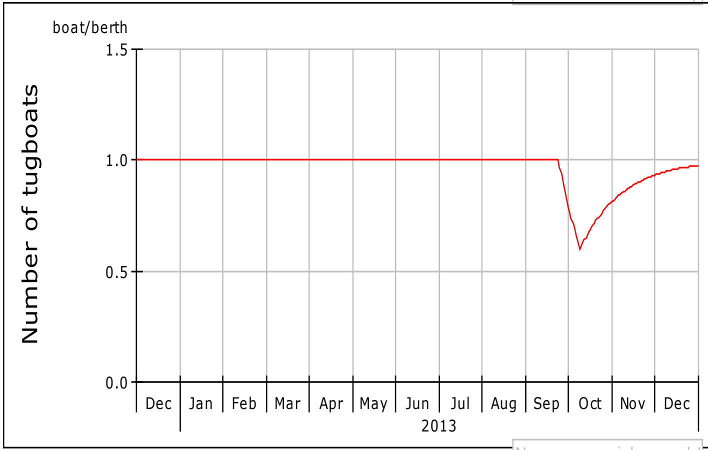
Time	Number_of_cranes (crane/berth)
Jan 01, 2013	1.00
Feb 01, 2013	1.00
Mar 01, 2013	1.00
Apr 01, 2013	1.00
May 01, 2013	1.00
Jun 01, 2013	1.00
Jul 01, 2013	1.00
Aug 01, 2013	1.00
Sep 01, 2013	1.00
Oct 01, 2013	0.79
Nov 01, 2013	0.81
Dec 01, 2013	1.12



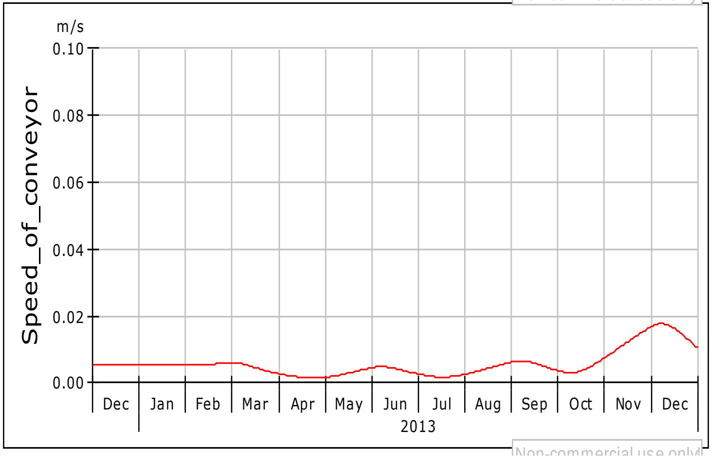
Time	Number_of_trucks (truck/berth)
Jan 01, 2013	6.00
Feb 01, 2013	6.00
Mar 01, 2013	6.60
Apr 01, 2013	6.42
May 01, 2013	6.64
Jun 01, 2013	6.87
Jul 01, 2013	7.68
Aug 01, 2013	8.52
Sep 01, 2013	8.26
Oct 01, 2013	4.45
Nov 01, 2013	1.90
Dec 01, 2013	4.18



Time	Number of tugboats (boat/berth)
Jan 01, 2013	1.00
Feb 01, 2013	1.00
Mar 01, 2013	1.00
Apr 01, 2013	1.00
May 01, 2013	1.00
Jun 01, 2013	1.00
Jul 01, 2013	1.00
Aug 01, 2013	1.00
Sep 01, 2013	1.00
Oct 01, 2013	0.79
Nov 01, 2013	0.81
Dec 01, 2013	0.93



Time	Speed_of_conveyor (m/s)
Jan 01, 2013	5.47e-3
Feb 01, 2013	5.47e-3
Mar 01, 2013	5.91e-3
Apr 01, 2013	2.75e-3
May 01, 2013	1.64e-3
Jun 01, 2013	4.52e-3
Jul 01, 2013	2.65e-3
Aug 01, 2013	2.60e-3
Sep 01, 2013	6.23e-3
Oct 01, 2013	3.67e-3
Nov 01, 2013	7.51e-3
Dec 01, 2013	0.02

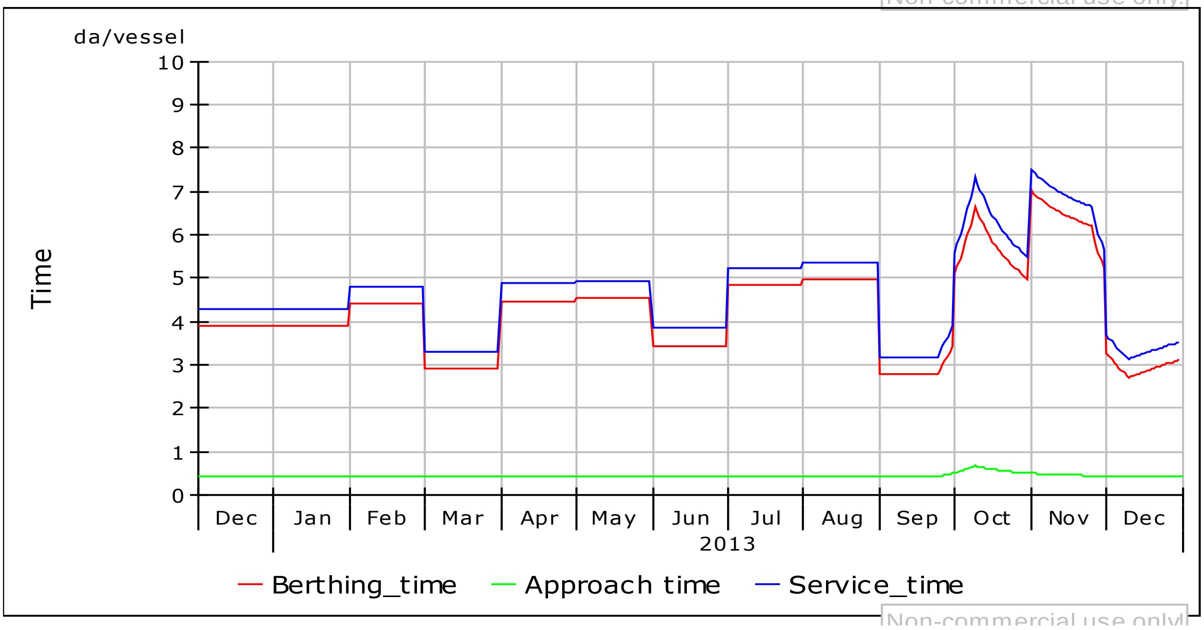


Once the number of the unloaded vessels is known and the vessel service time in Table 8, depending on the available equipment, is determined, the port's performance can be calculated.

Table 8. Simulation result of the vessel service time

(da/vessel)

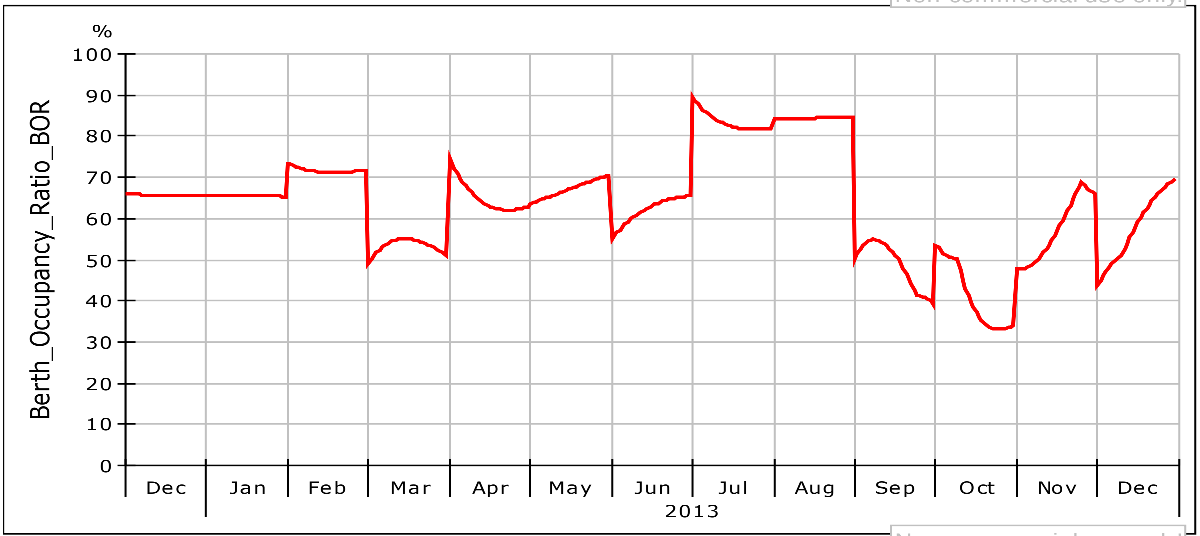
Time	Berthing_time	Approach time	Service_time
Jan 01, 2013	3.89	0.40	4.29
Feb 01, 2013	4.42	0.40	4.82
Mar 01, 2013	2.90	0.40	3.30
Apr 01, 2013	4.48	0.40	4.88
May 01, 2013	4.54	0.40	4.94
Jun 01, 2013	3.44	0.40	3.84
Jul 01, 2013	4.83	0.40	5.23
Aug 01, 2013	4.96	0.40	5.36
Sep 01, 2013	2.79	0.40	3.19
Oct 01, 2013	5.08	0.51	5.59
Nov 01, 2013	7.02	0.49	7.51
Dec 01, 2013	3.28	0.43	3.70

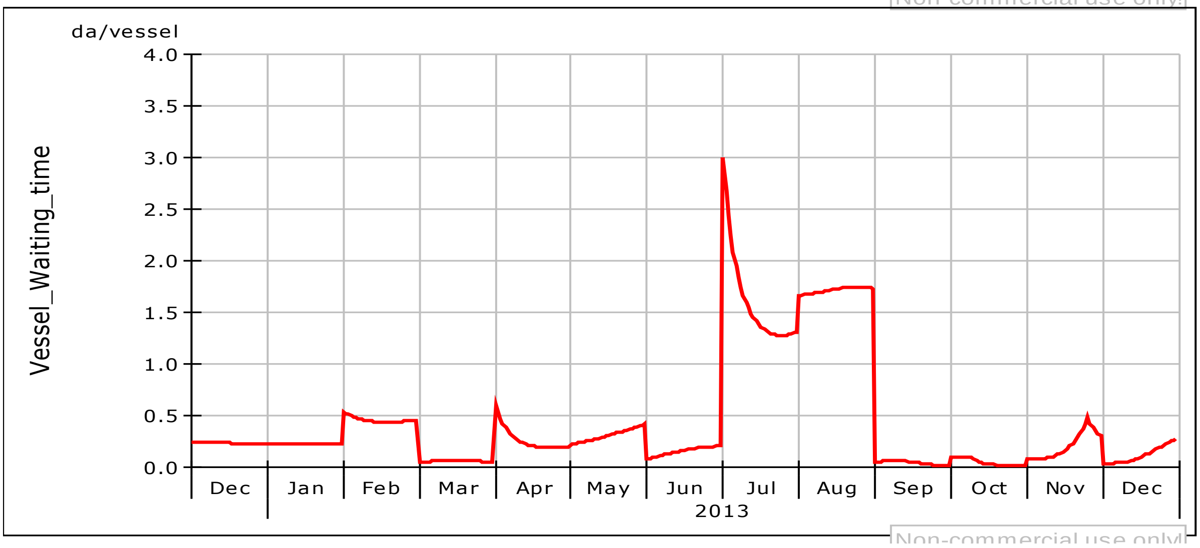


According to the simulation results in Table 9, the 89.29% berth occupancy ratio (BOR) was the highest value in July 2013, with vessel waiting times of 3 days per vessel. This was because the port terminal received many vessels whose load per vessel was high. In November 2013, the value of the BOR reached its low point while the service time reached the highest point. This was because the port terminal received a few vessels whose load per vessel was high.

Table 9. Simulation result of port operation performance indicators

Time	Berth_Occupancy_Ratio_BOR (%)	Vessel_Waiting_time (da/vessel)
Jan 01, 2013	65.66	0.23
Feb 01, 2013	73.42	0.53
Mar 01, 2013	49.18	0.04
Apr 01, 2013	74.48	0.60
May 01, 2013	63.75	0.22
Jun 01, 2013	55.00	0.07
Jul 01, 2013	89.29	3.00
Aug 01, 2013	84.02	1.66
Sep 01, 2013	50.20	0.04
Oct 01, 2013	53.59	0.09
Nov 01, 2013	47.80	0.07
Dec 01, 2013	43.93	0.02

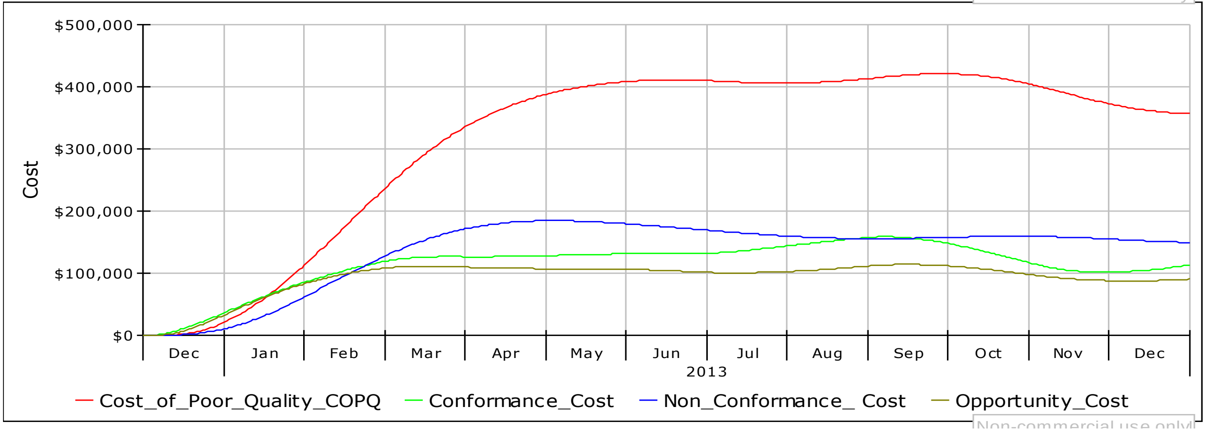




As depicted in Table 10, the cost of non-conformance was the highest cost among the other three cost factors of quality aspects, so the main point for improvement is to reduce the total non-conformance cost. The non-conformance cost is influenced by the internal and external failure costs. The greatest influence comes from the internal failure cost.

Table 10. Simulation results for cost of poor quality components

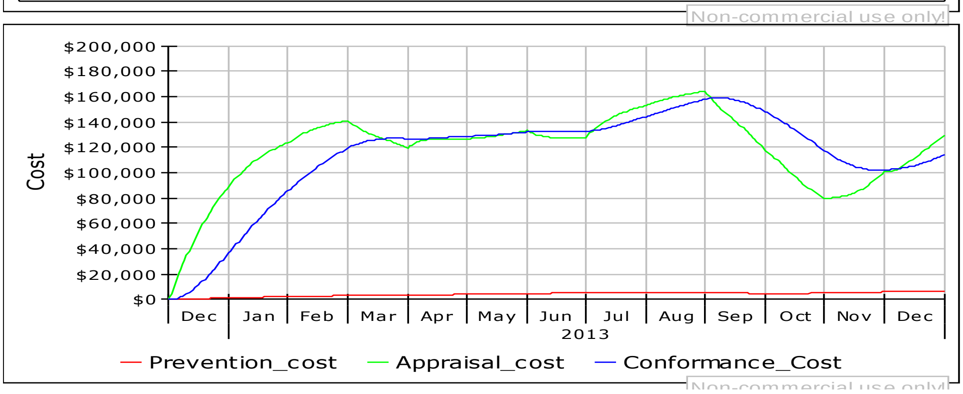
Time	Non_Conformance_ Cost	Conformance_Cost	Opportunity_Cost	Cost_of_Poor_Quality_COPQ
Jan 01, 2013	$10,746.67	$36,525.45	$32,992.37	$21,138.95
Feb 01, 2013	$62,359.26	$85,780.31	$83,445.35	$113,587.66
Mar 01, 2013	$128,138.77	$119,280.11	$108,517.93	$236,597.97
Apr 01, 2013	$171,527.20	$126,730.22	$110,057.15	$335,719.23
May 01, 2013	$184,674.30	$128,638.13	$107,399.66	$387,622.08
Jun 01, 2013	$179,728.48	$132,105.40	$106,304.04	$408,083.89
Jul 01, 2013	$169,500.26	$132,770.26	$101,722.47	$409,901.46
Aug 01, 2013	$160,030.75	$144,123.72	$102,991.07	$405,939.83
Sep 01, 2013	$155,828.72	$157,797.12	$111,945.50	$412,865.95
Oct 01, 2013	$157,926.72	$148,137.73	$112,003.57	$420,873.71
Nov 01, 2013	$159,582.91	$117,305.40	$98,205.55	$404,692.79
Dec 01, 2013	$155,314.45	$101,937.26	$88,520.19	$372,729.58



The resulting graphic of the prevention cost components that have the most effect on the conformance cost, as depicted in Table 11 below:

Table 11. Simulation results for conformance cost components

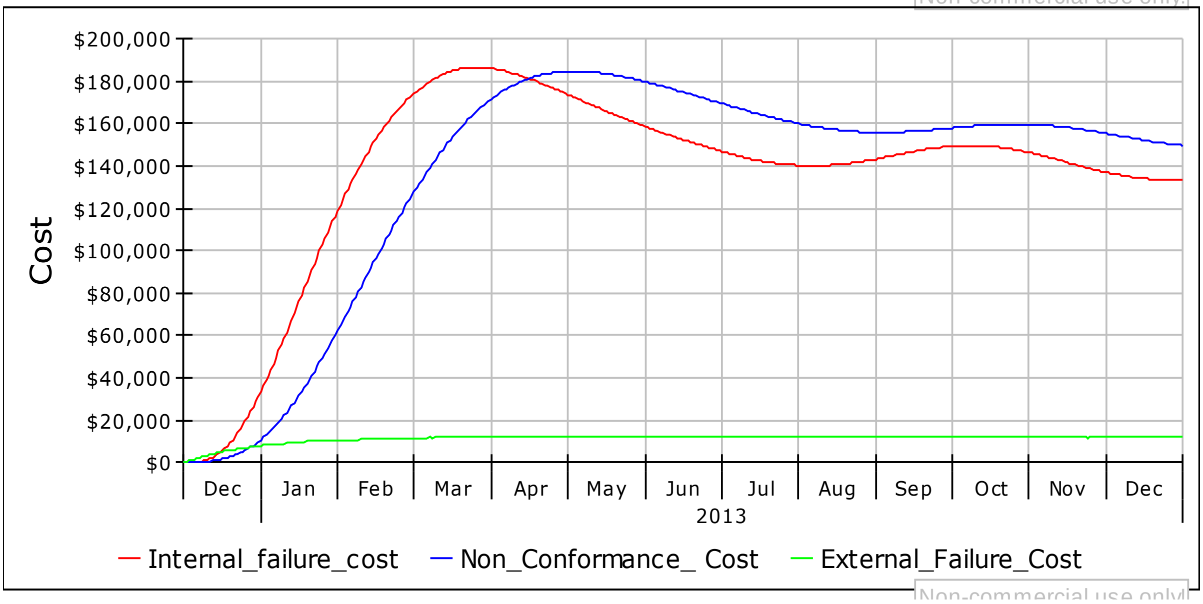
Time	Prevention_cost	Appraisal_cost	Conformance_Cost
Jan 01, 2013	$1,284.98	$89,107.95	$36,525.45
Feb 01, 2013	$2,330.02	$123,536.92	$85,780.31
Mar 01, 2013	$3,096.26	$141,006.23	$119,280.11
Apr 01, 2013	$3,613.57	$119,750.85	$126,730.22
May 01, 2013	$4,057.54	$126,623.47	$128,638.13
Jun 01, 2013	$4,646.42	$133,109.84	$132,105.40
Jul 01, 2013	$5,360.14	$127,696.68	$132,770.26
Aug 01, 2013	$5,575.82	$152,959.60	$144,123.72
Sep 01, 2013	$5,226.96	$164,149.66	$157,797.12
Oct 01, 2013	$4,922.44	$117,470.63	$148,137.73
Nov 01, 2013	$5,116.65	$79,857.26	$117,305.40
Dec 01, 2013	$6,054.40	$100,827.01	$101,937.26



The internal failure cost contributes most to the non-conformance cost. The components of the internal failure cost can be viewed in Table 12 below:

Table 12. Simulation results for non-conformance cost components

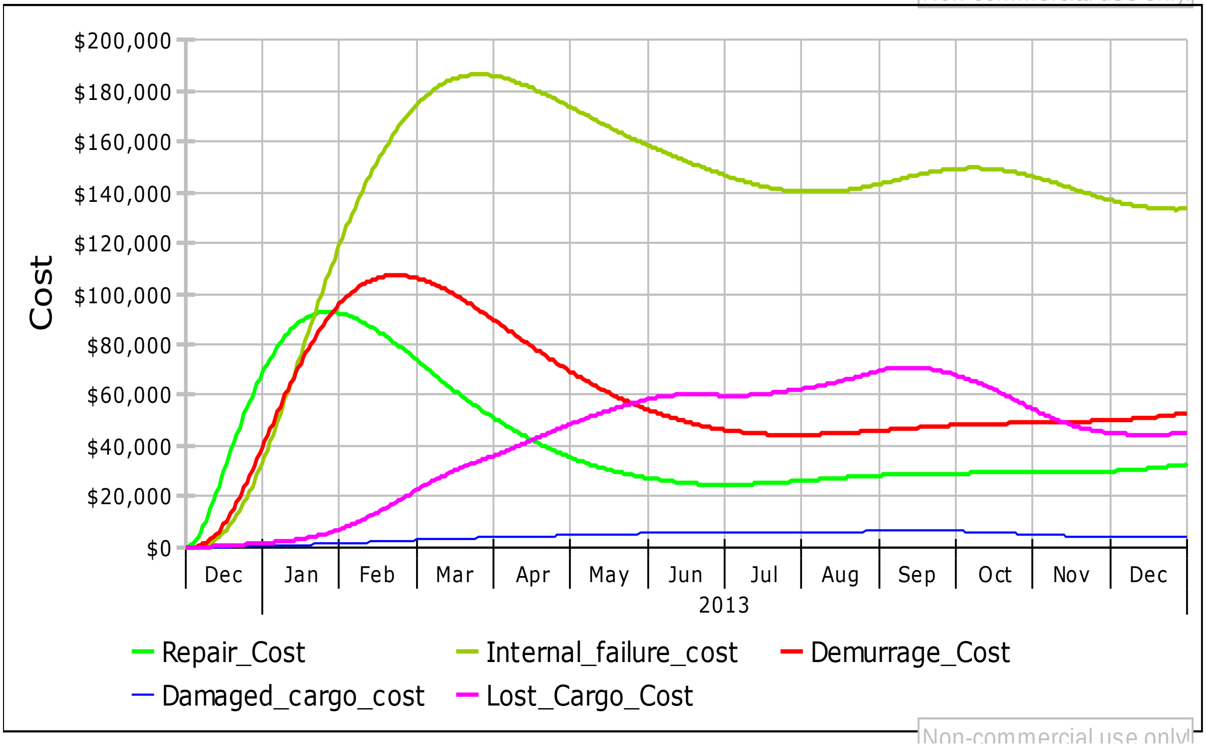
Time	Internal_failure_cost	External_Failure_Cost	Non_Conformance_ Cost
Jan 01, 2013	$33,451.71	$7,934.58	$10,746.67
Feb 01, 2013	$118,936.40	$10,396.51	$62,359.26
Mar 01, 2013	$174,444.70	$11,428.40	$128,138.77
Apr 01, 2013	$185,986.57	$12,367.16	$171,527.20
May 01, 2013	$173,700.90	$12,276.50	$184,674.30
Jun 01, 2013	$158,569.09	$12,108.25	$179,728.48
Jul 01, 2013	$146,767.78	$12,063.12	$169,500.26
Aug 01, 2013	$140,276.09	$12,234.90	$160,030.75
Sep 01, 2013	$143,158.62	$12,061.39	$155,828.72
Oct 01, 2013	$149,252.16	$12,280.66	$157,926.72
Nov 01, 2013	$146,310.10	$11,784.06	$159,582.91
Dec 01, 2013	$137,015.15	$11,857.71	$155,314.45



Based on Table 13, an improvement scenario is formulated to reduce these three cost factors simultaneously. According to the structure of the simulation model (Appendix B), the total demurrage cost is obtained from the total cost due to delay because of repair time and maintenance time of the transporter and equipment. The demurrage cost is the highest cost, followed by the repair cost and lost cargo cost as depicted in Table 13 below:

Table 13. Simulation result for internal failure cost components

Time	Repair_Cost	Lost_Cargo_Cost	Damaged_cargo_cost	Demurrage_Cost
Jan 01, 2013	$68,645.05	$1,589.22	$557.62	$39,361.29
Feb 01, 2013	$92,356.19	$6,979.98	$1,473.32	$95,800.48
Mar 01, 2013	$73,864.96	$22,521.54	$2,855.34	$106,212.30
Apr 01, 2013	$51,005.57	$36,008.25	$3,817.22	$89,693.31
May 01, 2013	$35,458.87	$48,493.71	$4,673.91	$69,224.01
Jun 01, 2013	$27,337.36	$58,298.65	$5,443.17	$54,294.74
Jul 01, 2013	$24,665.54	$59,841.59	$5,574.55	$46,291.65
Aug 01, 2013	$26,200.32	$62,474.26	$5,705.37	$44,379.23
Sep 01, 2013	$28,314.40	$69,462.58	$6,404.53	$45,999.96
Oct 01, 2013	$29,214.72	$67,918.93	$6,339.02	$48,132.74
Nov 01, 2013	$29,296.11	$54,618.05	$5,055.67	$49,138.51
Dec 01, 2013	$29,974.99	$45,143.21	$4,130.06	$50,053.28



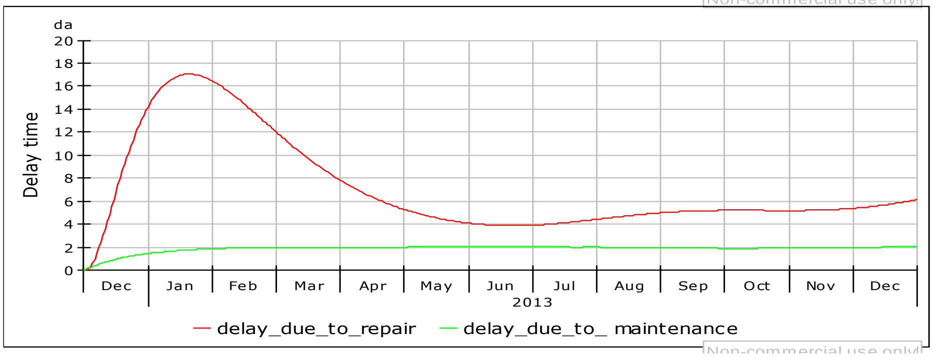
All internal failure costs are significantly increased, except the damaged cargo cost. The behavior of the internal failure costs shows growth with overshoot because the system tries to achieve the target due to delay factors in the system. The target of the internal failure costs relates to the value of cost of poor quality (COPQ) that compared with the sales revenue. The feedback of the COPQ to the prevention and appraisal costs needs the time delay based on the decision makers.

The delay due to repair induces the high demurrage cost as depicted in Table 14 below.

Table 14. Comparison between delay due to maintenance and delay due to repair

(da)

Time	delay_due_to_repair	delay_due_to_ maintenance
Jan 01, 2013	14.20	1.45
Feb 01, 2013	16.46	1.86
Mar 01, 2013	12.01	1.97
Apr 01, 2013	7.82	1.97
May 01, 2013	5.27	2.00
Jun 01, 2013	4.10	2.05
Jul 01, 2013	3.90	2.05
Aug 01, 2013	4.42	2.01
Sep 01, 2013	4.99	1.90
Oct 01, 2013	5.20	1.89
Nov 01, 2013	5.18	1.94
Dec 01, 2013	5.38	1.99

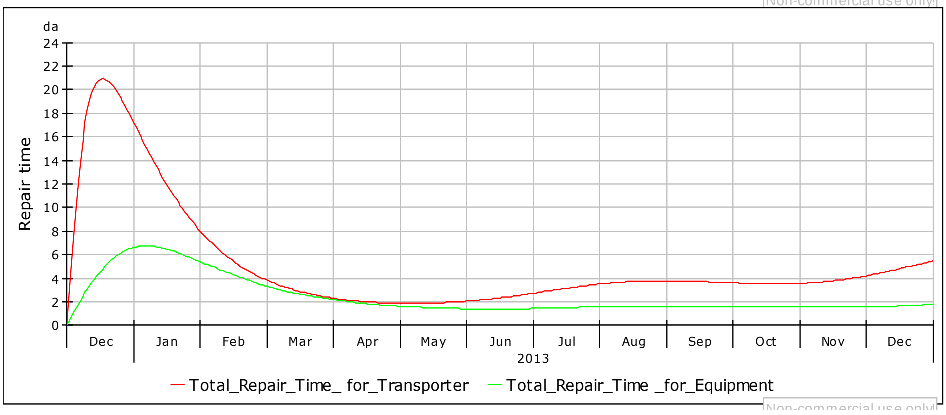


Furthermore, delay due to repair is directly influenced by the total repair time after transporter and equipment breakdown. As presented in Table 15, the total repair time for the transporter is responsible for the high demurrage cost.

Table 15. Comparison between repair time of transporter and equipment

(da)

Time	Total_Repair_Time_ for_Transporter	Total_Repair_Time _for_Equipment
Jan 01, 2013	17.18	6.61
Feb 01, 2013	8.00	5.39
Mar 01, 2013	3.83	3.31
Apr 01, 2013	2.30	2.19
May 01, 2013	1.89	1.62
Jun 01, 2013	2.05	1.42
Jul 01, 2013	2.73	1.44
Aug 01, 2013	3.51	1.56
Sep 01, 2013	3.79	1.60
Oct 01, 2013	3.63	1.62
Nov 01, 2013	3.56	1.62
Dec 01, 2013	4.21	1.62

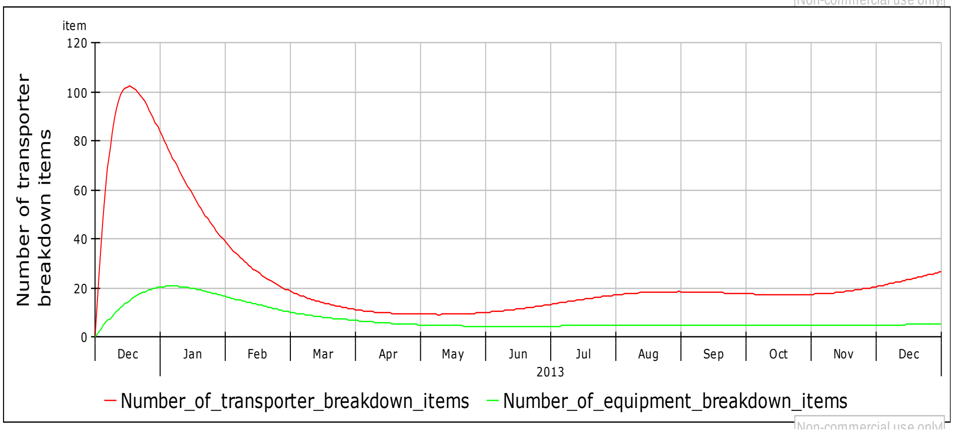


The total repair time for the transporter contributes most to the total repair time. As a result, the high repair cost must also be affected by transporter breakdown, as shown in detail in Table 16, because the only positive causal relations of the total repair cost are from the number of transporter and equipment breakdowns.

Table 16.Comparison between number of transporter and equipment breakdowns

(item)

Time	Number_of_transporter_breakdown_items	Number_of_equipment_breakdown_items
Jan 01, 2013	83.99	20.35
Feb 01, 2013	39.11	16.59
Mar 01, 2013	18.72	10.19
Apr 01, 2013	11.24	6.75
May 01, 2013	9.26	4.99
Jun 01, 2013	10.04	4.36
Jul 01, 2013	13.34	4.44
Aug 01, 2013	17.18	4.80
Sep 01, 2013	18.55	4.93
Oct 01, 2013	17.72	4.97
Nov 01, 2013	17.42	4.99
Dec 01, 2013	20.60	5.00



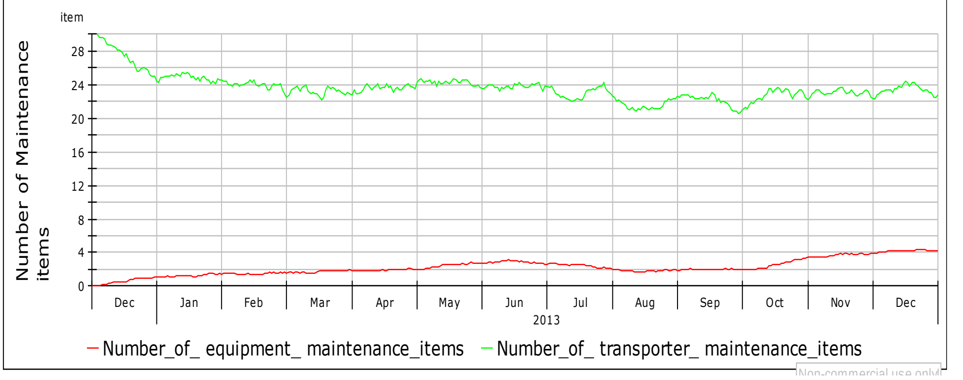
The model component that affects the demurrage and repair cost is the total number of transporter breakdowns, which is mainly influenced by the transporter maintenance cost through the number of transporter maintenance items. The number of transporter maintenance items should be increased to reduce the number of transporter breakdowns. There are such large values in the beginning for the behavior of the delay due to repair, the total repair time, and the number of transporter and equipment breakdown items. This condition depends on the warming up of the simulation and the delay time of the feedback from decision makers.

On the other hand, the total lost cargo cost is only affected by the fluctuation of the safety and security cost and cargo inspection cost. The combination of increasing both the safety and security budget and the number of inspectors per vessel should reduce the lost cargo. In Table 17, the number of transporter maintenance items contributes most to preventive maintenance.

Table 17. Number of equipment and transporter maintenance items

(item)

Time	Number_of_ equipment_ maintenance_items	Number_of_ transporter_ maintenance_items
Jan 01, 2013	1.09	24.47
Feb 01, 2013	1.47	24.51
Mar 01, 2013	1.60	22.41
Apr 01, 2013	1.90	22.82
May 01, 2013	2.01	24.24
Jun 01, 2013	2.79	23.58
Jul 01, 2013	2.65	23.77
Aug 01, 2013	2.04	22.65
Sep 01, 2013	1.90	22.60
Oct 01, 2013	1.99	20.98
Nov 01, 2013	3.44	22.18
Dec 01, 2013	3.87	22.36



6.4 Validation Process

Once the model has been developed and simulated, the results of simulation have to be validated. Validation processes in system dynamics simulation had been carried out by discussing with experts and applying statistical methods. The process of validation should be conducted by using some tests to make the base case simulation model acceptable and credible. According to Sterman (2000), the purpose of the test was to improve the model from flaws. The seven primary tests that had been done to the base case of six sigma model in ports are as follows:

1. **Boundary Adequacy**

   The boundary adequacy test is important because it considers every variable that is needed to develop the required model (Sterman, 2000). The model of the port operation in the bulk port terminal has two sub-models, of the sea side and the land side, that include all the necessary variables to develop the expected model of the port operation in the dry bulk port terminal. A stock flow diagram and a causal loop diagram have been constructed and discussed with experts in the real case. The concept of this model is to identify the change of behavior of the system over time due to dynamic conditions. With the help of this model, the interaction of each variable can be analyzed over time. The output of the model will also change when the parameters of the exogenous variables are changed.

The case study in the reference model according to Briano et al. (2009) was intended to analyze the material flow without considering a feedback loop (for example, the number of cranes as an exogenous variable). When the feedback loop in the modified model was developed, the required number of cranes became an endogenous variable.

The boundary of the model is the scope of the cost of quality implementation in the port business, including the cost factors considered. The border is made clear using a causal loop diagram and a stock flow diagram. This test is done by not only conducting an interview with the system expert and key participants, but also reviewing related literature and examining the data from the company. A recalculation of the software output is also done to ensure that the model represents the real condition as closely as possible.

2. **Structure Assessment**

   The model is constructed to recreate the behavior of operations in the dry bulk terminal. The reference model is necessary for the expected model. The model was modified from the model of operation in a container port terminal by Briano et al. (2009), the model of inventory management by Sterman (2000), and the model of cost factors by Kiani et al. (2006). Interviews and discussions with experts were conducted during the creation of the model. The model provided decision variables that have to be decided on by the actors. For example, the time adjustment to correct the rate of stocks in the warehouse can be adjusted by an actor so that policy designs can be implemented in the model. The structure of the model is consistent and closely depicts the real system. All the values in the stock and flow diagram make sense, which means that there are no negative values for all the real quantities contained in the model, such as the number of transporters, the amount of equipment, costs, and so on.

3. **Dimensional Consistency**

   The dimensional consistency test verifies every dimension of the variables (Martis, 2006). Every parameter of the variables in the model is checked one by one. The units in the auxiliary variables occur due to the formulation of other constant variables and auxiliary variables. The model will not give correct output if the unit does not fit the related variables.

4. **Parameter Assessment**

   The input parameters of the model are proved before they are used in the model. A statistical method is used to get appropriate input variables. For example, there is a mathematical correlation between the berth occupancy ratio and the delay factor. The relationship is determined by the second term exponential based on Monie (1987) with the adjusted R-squared value of 0.9994. This relationship is determined by data fitting technique that is generated using Matlab© software. Moreover, estimations of input parameters are also necessary to solve the problems with the model. The parameters in the base case model variables were taken using a numerical calculation from the company, especially for the constant values, with interviews and expert opinion for defining the relationship of each related variable.

5. **Extreme Condition**

This test was done by changing the input parameter of the operation cycle of the truck to zero. The result of the extreme condition test is shown in Figure 70 below:

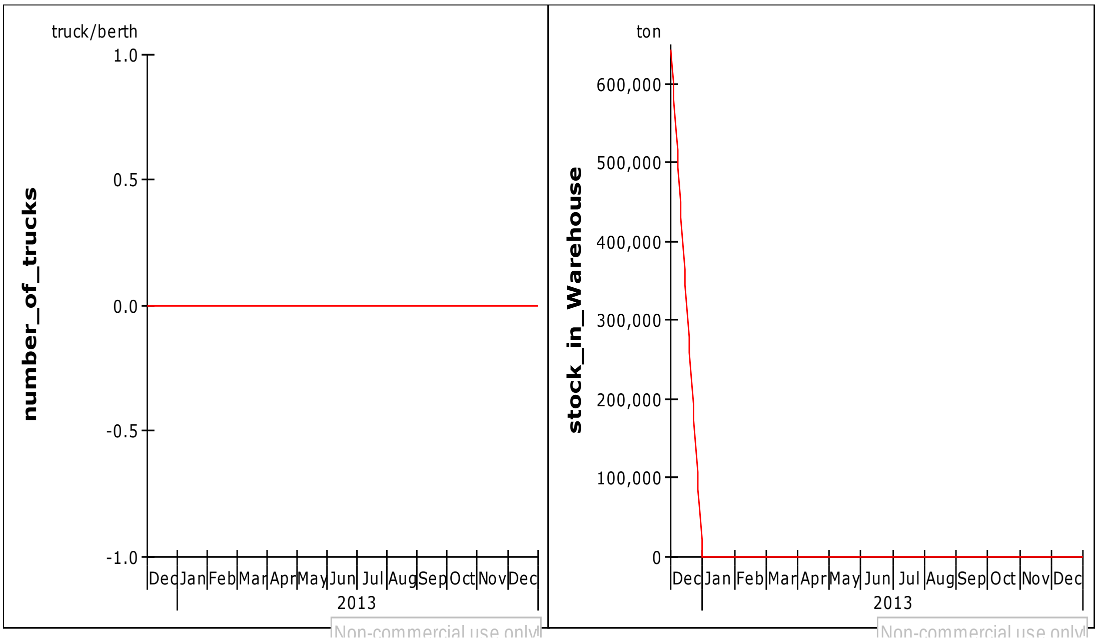


Figure 70. Result of the extreme condition test

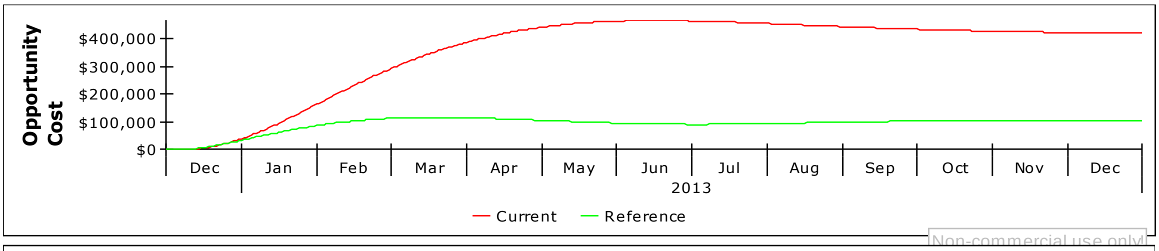
Using a value of zero for the operation cycle of trucks describes the situation where there is no truck operating in the dry bulk port terminal so that also no goods can be stocked in the warehouse.

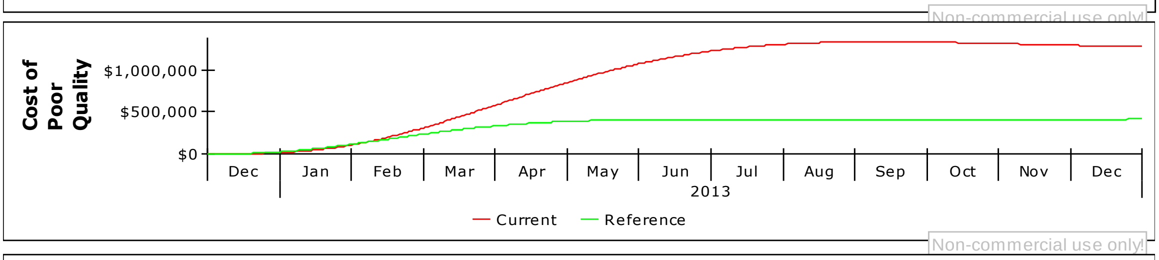
Also, the extreme condition test for the port quality level sub-system is done to observe whether there are negative values in certain variables that yield misleading output or prevent the simulation running improperly. This is done by putting in some small random values (greater than zero) and very high values of the related endogenous variables. Table 18 shows the Powersim output if the amount of cargo = 0 and all the maintenance items = 0. From this picture, it is found that the model does not produce any negative values, so it can be concluded that the model is robust through the extremely low input.

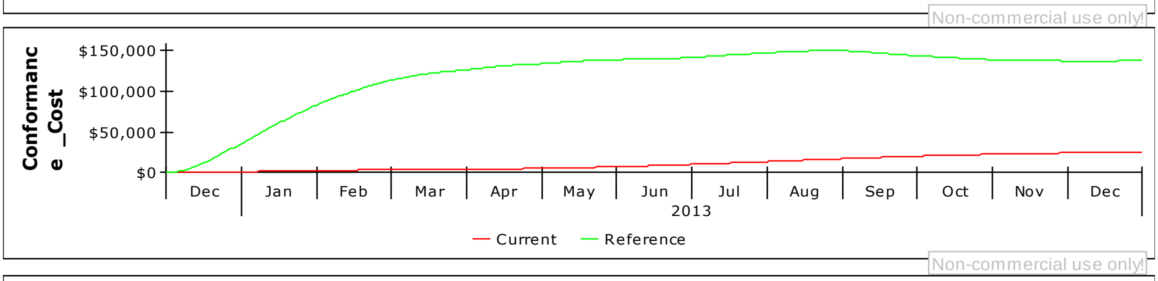
In Table 18 below, the pattern of the logical aspects is shown, where the current graphs represent the extreme low condition while the normal model condition is used as a reference. When the conformance cost increases, the non-conformance cost automatically decreases, while the opportunity cost accommodates the unavailability calculation in both the non-conformance and conformance costs. In conclusion, the model is logical and robust in conditions of extreme low input.

Table 18. Simulation output of zero cargo and maintenance items

Time	ConformanceCost	NonConformanceCost	Opportunity Cost	Cost of Poor Quality
Dec 01, 2012	$0.00	$0.00	$0.00	$0.00
Jan 01, 2013	$1,147.86	$11,710.21	$39,125.97	$11,277.96
Feb 01, 2013	$2,660.88	$94,017.29	$163,763.08	$105,138.72
Mar 01, 2013	$3,611.11	$264,882.37	$294,029.60	$311,317.09
Apr 01, 2013	$4,169.82	$472,868.85	$388,310.38	$583,131.95
May 01, 2013	$4,455.48	$663,113.83	$445,383.30	$856,510.99
Jun 01, 2013	$4,530.18	$808,985.15	$476,473.29	$1,087,872.87
Jul 01, 2013	$4,528.55	$908,352.74	$492,270.15	$1,261,404.46
Aug 01, 2013	$4,536.03	$970,300.98	$499,909.71	$1,380,304.53
Sep 01, 2013	$4,595.29	$1,006,263.52	$503,470.57	$1,456,124.95
Oct 01, 2013	$4,612.90	$1,026,381.44	$505,083.59	$1,501,860.64
Nov 01, 2013	$4,574.82	$1,037,089.97	$505,797.81	$1,528,221.73
Dec 01, 2013	$4,566.44	$1,042,387.79	$506,108.22	$1,542,731.06
Jan 01, 2014	$4,609.54	$1,045,185.18	$506,241.06	$1,550,484.44







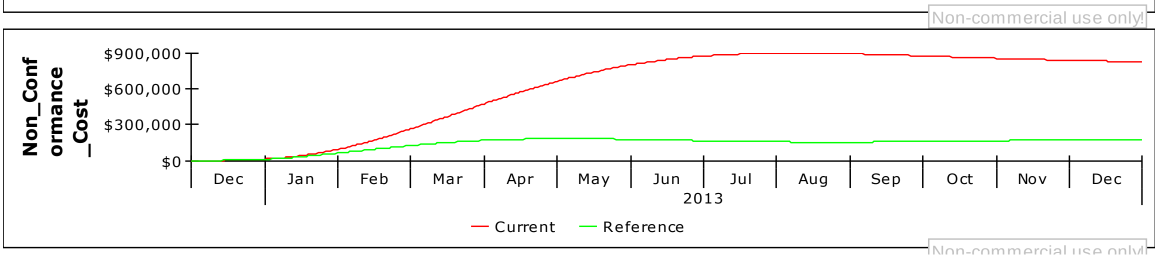
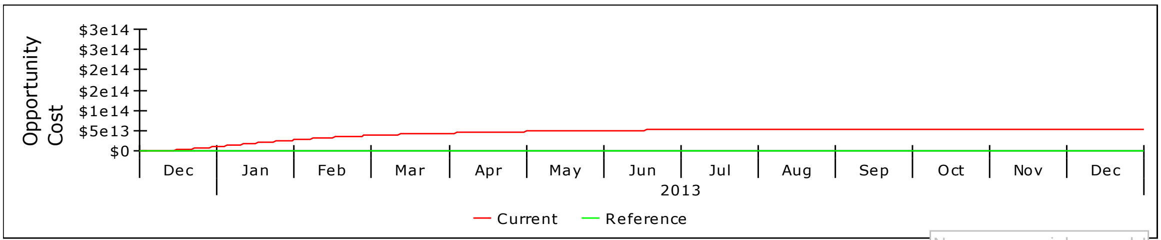
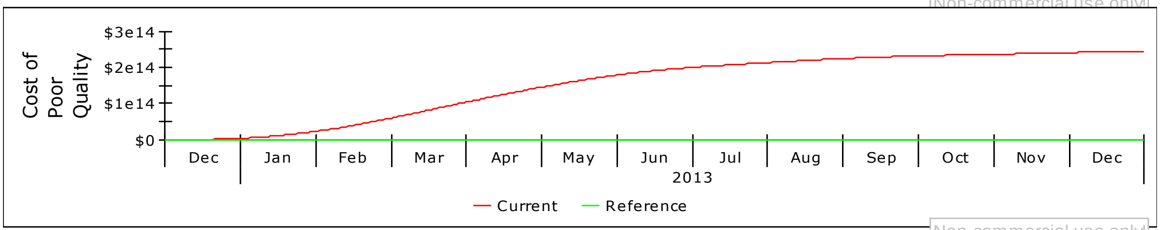


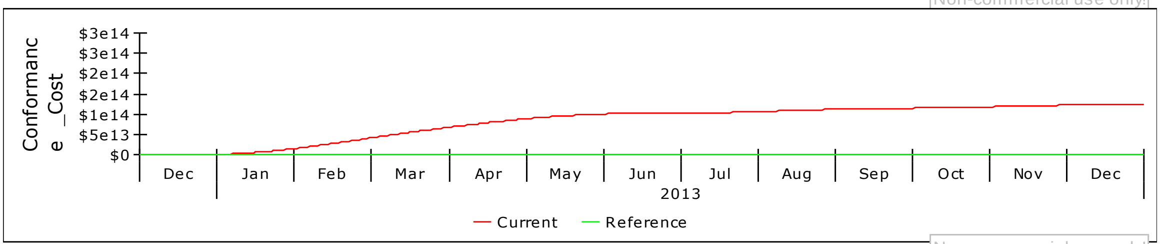
Table 19 presents the model output if the amount of cargo becomes very large (100,000,000,000,000 ton) and there are also 100,000,000,000,000 items each of transporter and equipment maintenance per month. The table and graph below show the difference between the model condition in the extreme high input (current) and normal model (reference) conditions. The model does not produce any negative values, and the graphics for the output are still logical. If the input of the amount of cargo and equipment and transporter maintenance items is very high, the model can run normally and the result is very high. So it can be concluded that the model is robust through the extremely high input.

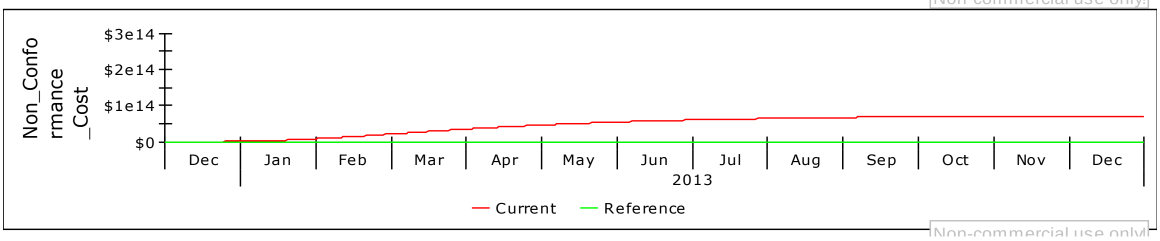
Table 19. Simulation output of very large cargo, transporter, and equipment maintenance items

Time	Non_Conformance _Cost	Conformance _Cost	Opportunity Cost	Cost of Poor Quality
Dec 01, 2012	$0.00	$0.00	$0.00	$0.00
Jan 01, 2013	$936,083,873,359.57	$1.84e12	$1.17e13	$3.86e12
Feb 01, 2013	$8.06e12	$1.61e13	$2.81e13	$2.32e13
Mar 01, 2013	$2.11e13	$4.27e13	$3.92e13	$6.00e13
Apr 01, 2013	$3.49e13	$6.82e13	$4.48e13	$1.04e14
May 01, 2013	$4.61e13	$8.92e13	$4.88e13	$1.46e14
Jun 01, 2013	$5.43e13	$1.01e14	$5.14e13	$1.79e14
Jul 01, 2013	$6.01e13	$1.03e14	$5.28e13	$2.00e14
Aug 01, 2013	$6.40e13	$1.07e14	$5.49e13	$2.14e14
Sep 01, 2013	$6.70e13	$1.12e14	$5.48e13	$2.25e14
Oct 01, 2013	$6.85e13	$1.15e14	$5.37e13	$2.32e14
Nov 01, 2013	$6.88e13	$1.18e14	$5.37e13	$2.36e14
Dec 01, 2013	$6.88e13	$1.22e14	$5.44e13	$2.41e14
Jan 01, 2014	$6.92e13	$1.23e14	$5.54e13	$2.45e14









6. Integration Error

According to Sterman (2000), a numerical integration method and a time step are the key to system dynamics modelling. Selecting different numerical integration methods and setting different ranges of the time step should not change the simulation results significantly. Figure 71 shows that there are no significant changes in the value of berth occupancy when setting different time steps between 0.3 days and 10 days. This indicates that the model can be accepted.

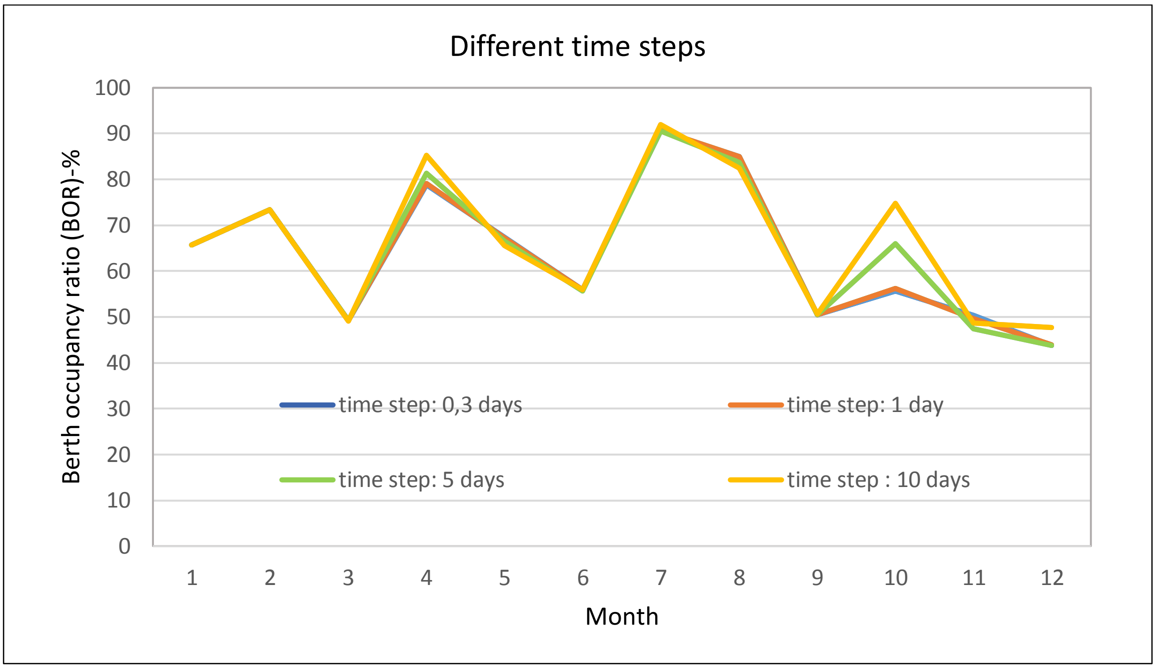


Figure 71. The result of the integration error test by setting different values of time steps

From Figure 72, the integration error test shows that there are no significant changes in the value of the berth occupancy ratio when selecting different types of integration. This indicates that the model can be accepted.

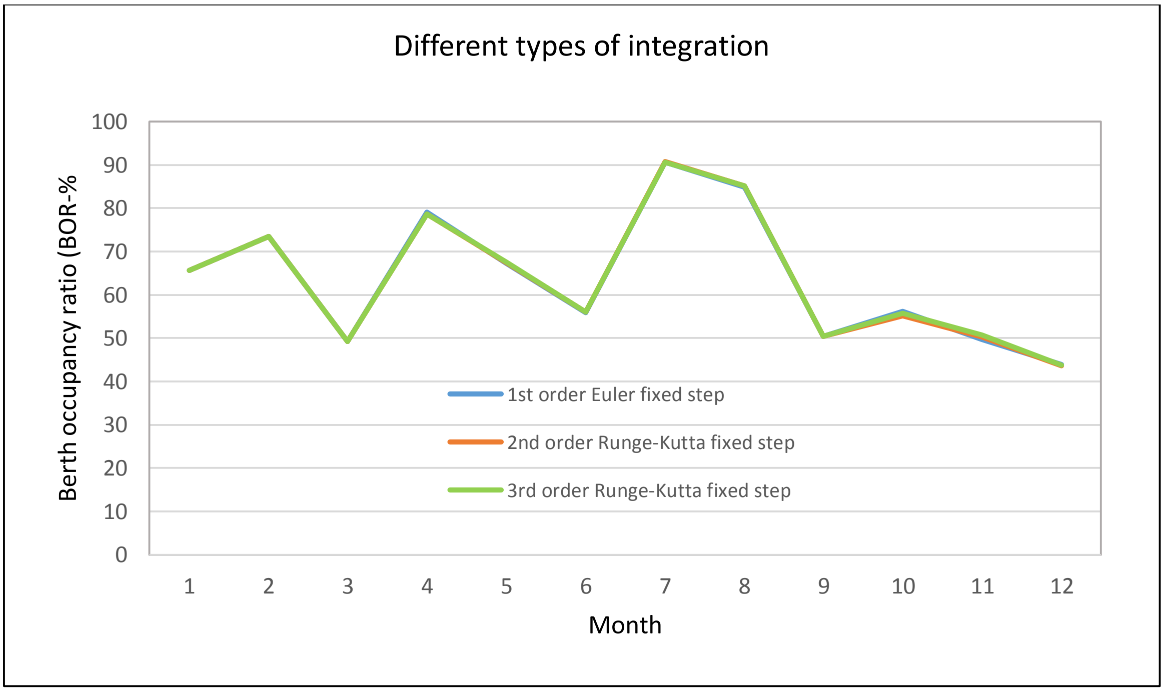


Figure 72. The result of integration error test by selecting different type of integrations

Also, as concerns the port quality level sub-system, this model is evidently not sensitive to the choice of time step using the numerical integration process test. The base case model is run with a 1 day time step which is then cut in half to 0.5 day to test this integration error. Table 20 shows the simulation result in timetable form, while Figure 73 shows the difference between these different time steps in graphic form.

Table 20. Simulation output for the port quality level: a) time step 0.5 day; b) time step 1 day

Time	Non_Conformance _Cost	Conformance _Cost	Opportunity Cost	Cost of Poor Quality
Dec 01, 2012	$0.00	$0.00	$0.00	$0.00
Jan 01, 2013	$11,099.78	$37,942.89	$34,088.72	$63,520.77
Feb 01, 2013	$60,516.76	$83,057.79	$90,861.89	$86,692.66
Mar 01, 2013	$123,915.53	$108,676.54	$118,750.49	$95,145.58
Apr 01, 2013	$168,031.80	$124,492.59	$123,712.62	$98,229.15
May 01, 2013	$185,704.98	$131,752.77	$117,962.26	$99,354.01
Jun 01, 2013	$184,764.54	$134,904.37	$109,940.37	$99,764.35
Jul 01, 2013	$174,972.02	$136,742.73	$103,703.61	$99,914.04
Aug 01, 2013	$163,447.24	$137,583.35	$100,590.95	$99,968.64
Sep 01, 2013	$154,238.70	$139,014.93	$100,757.93	$99,988.56
Oct 01, 2013	$148,451.29	$138,949.17	$100,368.48	$99,995.83
Nov 01, 2013	$145,074.43	$138,494.35	$99,413.58	$99,998.48
Dec 01, 2013	$142,947.30	$138,788.57	$98,526.67	$99,999.44
Jan 01, 2014	$141,333.09	$139,250.25	$96,734.86	$99,999.80

a)

Time	Non_Conformance _Cost	Conformance _Cost	Opportunity Cost	Cost of Poor Quality
Dec 01, 2012	$0.00	$0.00	$0.00	$0.00
Jan 01, 2013	$10,812.16	$34,165.91	$34,810.94	$63,833.85
Feb 01, 2013	$63,535.38	$77,754.21	$97,152.25	$86,920.09
Mar 01, 2013	$133,590.52	$107,066.19	$129,243.40	$95,269.50
Apr 01, 2013	$182,675.81	$124,524.66	$131,963.10	$98,289.16
May 01, 2013	$200,809.29	$130,313.92	$120,195.11	$99,381.26
Jun 01, 2013	$196,327.81	$130,204.50	$108,768.21	$99,776.22
Jul 01, 2013	$183,040.87	$133,353.39	$103,437.56	$99,919.07
Aug 01, 2013	$170,422.15	$136,466.13	$102,072.58	$99,970.73
Sep 01, 2013	$162,556.97	$135,706.59	$103,619.89	$99,989.41
Oct 01, 2013	$159,859.03	$134,514.04	$106,941.33	$99,996.17
Nov 01, 2013	$159,718.73	$132,847.18	$106,196.78	$99,998.62
Dec 01, 2013	$158,701.39	$133,294.41	$103,051.68	$99,999.50
Jan 01, 2014	$156,358.28	$136,474.37	$102,736.66	$99,999.82

b)

Accordingly, Figure 73 shows that there are no significant changes in the value of cost components when setting different time steps between 0.5 day and 1 day. In the graphics, the red line (current) represents the model output with a time step of 0.5 day, and the green line (reference) is the model output for a time step of 1 day.

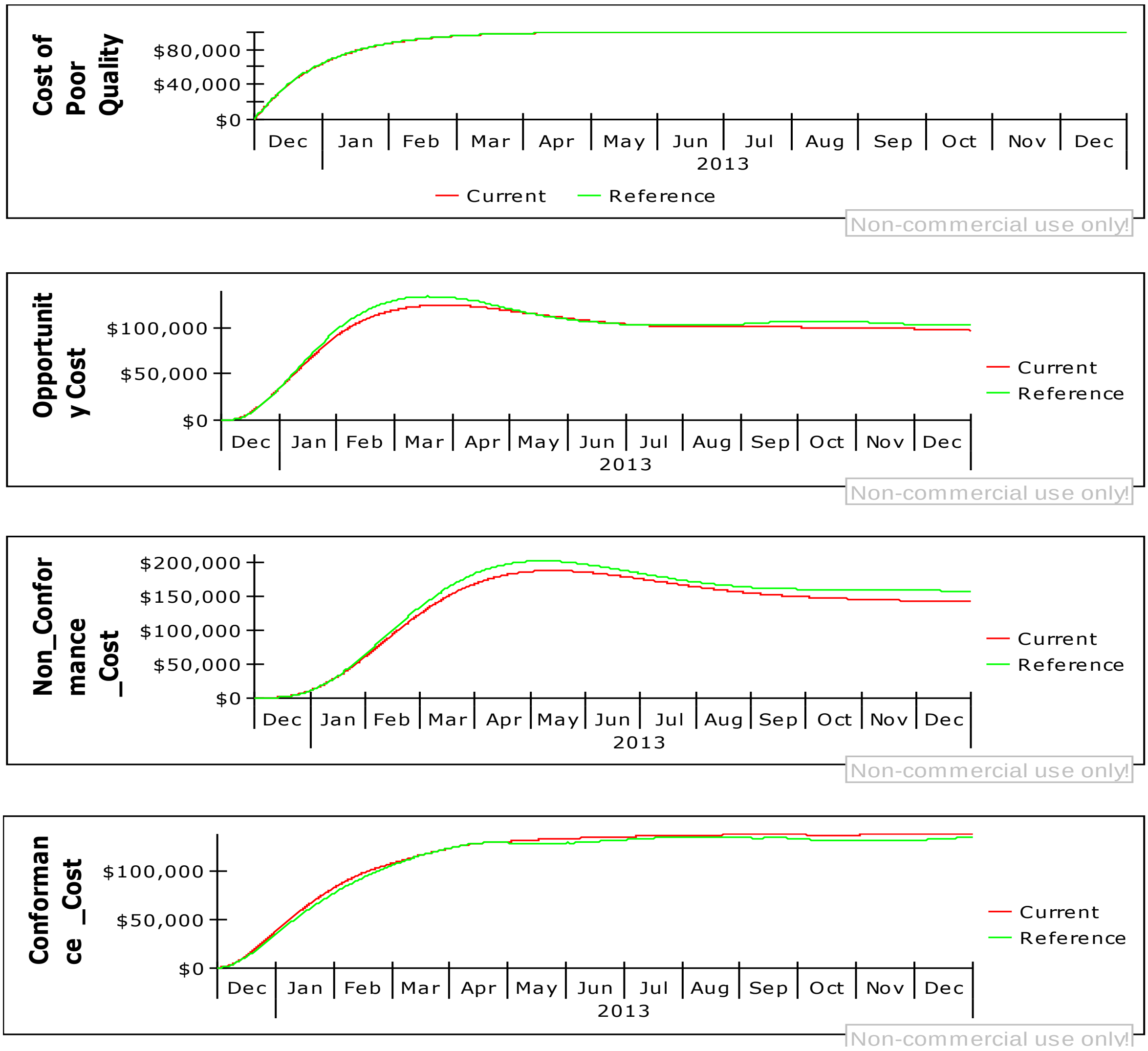


Figure 73. Graphics for integration error test for the port quality level by setting different values of time steps

7. Behavior Reproduction

Statistical validation of the model is done to prove whether the model simulation results differ much from the actual model. All the outputs (calculation and simulation) are normally distributed and tested using the independent two-sample t-test (α=0.05) using MS Excel with the hypothesis:

H_0: $\mu_1 = \mu_2$, meaning the two groups have no differences with respect to their mean values

H_1: $\mu_1 \neq \mu_2$, meaning the two groups have differences with respect to their mean values

where μ_1 is the simulation output, and μ_2 is the actual calculation output.

If the test result shows an absolute t-stat value of each group that is smaller than the t-critical two-tailed value, this means that H1 should be rejected; in other words the average values of both groups show no differences. The t-stat value is calculated by the formulation below:

$$t - stat = \frac{(\bar{x} - \bar{y}) - (\mu_x - \mu_y)}{s\sqrt{\frac{1}{n_x} + \frac{1}{n_y}}} \tag{6.1}$$

$$s^2 = \frac{(n_x - 1)s_x^2 + (n_y - 1)s_y^2}{(n_x - 1) + (n_y - 1)} \tag{6.2}$$

The t-critical value is determined by t table based on the degree of freedom, df, and degree of confidence, α.

The validation process was conducted in two sub-systems:

1. **The port operation sub-system.**

   The validation process was conducted for the port operation sub-system. The tests are done for several primary port operation variables in the model, such as the number of unloaded vessels, berth occupancy ratio, vessel service time, vessel waiting time, throughput in the warehouse, and throughput in the stockpile yard. Summary of the t-test results for several variables in the port operation can be seen in Table 21:

   Table 21. The t-test results for several primary port operation variables

No.	Variables	Absolute t-stat	t-critical	H_0
1	Number of unloaded vessels	1.38	2.10	Accepted
2	Berth occupancy ratio (BOR)	0.91	2.08	Accepted
3	Vessel service time	0.58	2.11	Accepted
4	Vessel waiting time	1.33	2.20	Accepted
5	Throughput in the warehouse	0.05	2.07	Accepted
6	Throughput in the stockpile yard	0.01	2.07	Accepted

   Based on Table 21, all the results showed that there are no differences between the actual and the simulation results.

2. **The Port Quality Level sub-system**

   The validation process was conducted for the port quality level sub-system. The tests are done for several main cost components in the model, such as the internal failure cost, external failure cost, non-conformance cost, appraisal cost, prevention cost, conformance cost, opportunity cost, and cost of poor quality. Summary of the t-test results for several variables in the port quality level can be seen in Table 22:

Table 22. The t-test results for several primary port quality level variables

No	Variables	Absolute t-stat	t-critical	H_0
1	Internal failure cost	0.11	2.07	Accepted
2	External failure cost	1.99	2.09	Accepted
3	Non-conformance cost	0.65	2.09	Accepted
4	Appraisal cost	0.95	2.09	Accepted
5	Prevention cost	1.27	2.07	Accepted
6	Conformance cost	1.35	2.08	Accepted
7	Opportunity cost	1.88	2.09	Accepted
8	Cost of poor quality (COPQ)	1.03	2.16	Accepted

Based on Table 22, all the results showed that there are no differences between the actual and the simulation results.

6.5 Measuring the Baseline Performance of the Model

The baseline performance of the six sigma model is measured to improve the lean supply chain in ports using the performance metrics of six sigma tools. The sigma value, the process capability indices, and the cost of poor quality were selected as six sigma tools to measure the baseline performance. The sigma value and process capability indices related to the lost cargo, damaged cargo, delay of equipment and transporter, and transporter and equipment breakdown. The cost of poor quality was utilized for the activities that related to the poor quality. Figure 74 shows the performance metrics used to measure waste in ports:

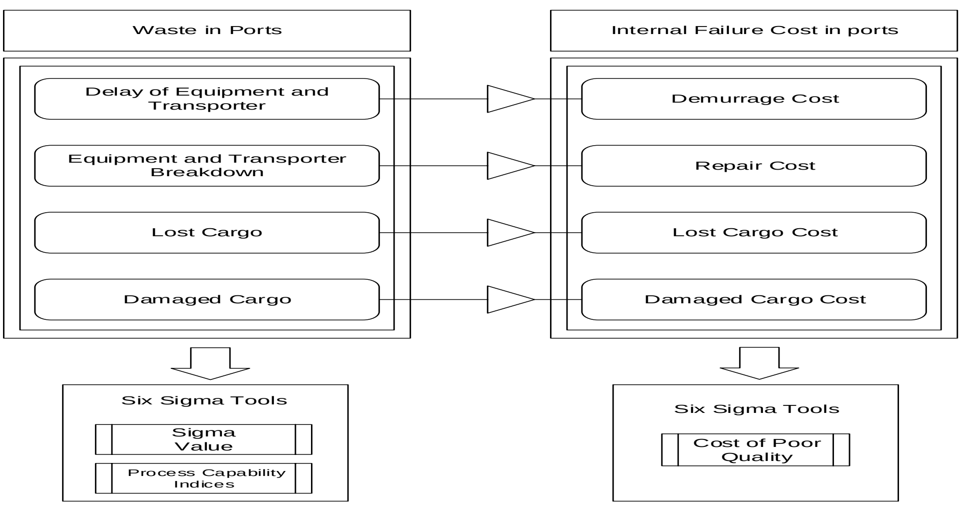


Figure 74. Performance metrics to measure waste in ports

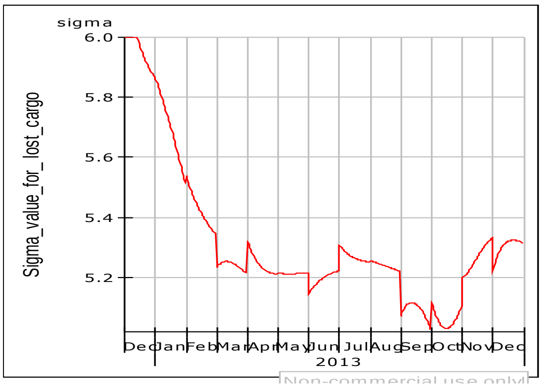
The simulation results of the performance metrics of six sigma tools are based on the base simulation as follows:

1. **The sigma value (SV) and the process capability indices (Cpk)**

   These metrics are chosen to measure the baseline performance of the lost cargo, damaged cargo, equipment breakdown, transporter breakdown, and delay time.

   Table 23. Sigma value and process capability indices (Cpk) of the lost cargo

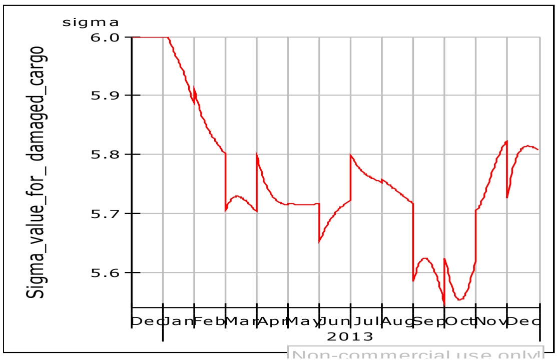
Time	Sigma_value_for_ lost_cargo (sigma)	Cpk_of_lost_cargo (Cpk)
Jan 01, 2013	5.86	1.95
Feb 01, 2013	5.54	1.85
Mar 01, 2013	5.23	1.74
Apr 01, 2013	5.32	1.77
May 01, 2013	5.22	1.74
Jun 01, 2013	5.15	1.72
Jul 01, 2013	5.31	1.77
Aug 01, 2013	5.26	1.75
Sep 01, 2013	5.07	1.69
Oct 01, 2013	5.12	1.71
Nov 01, 2013	5.20	1.73
Dec 01, 2013	5.22	1.74

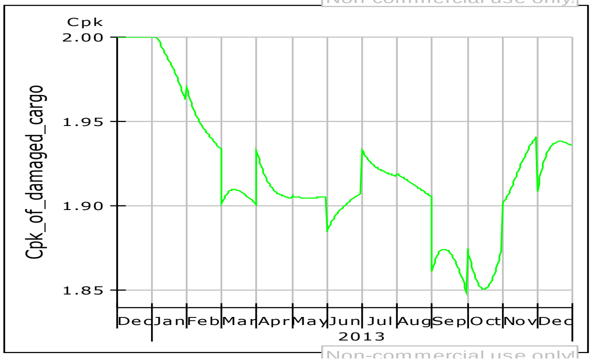


   From Table 23 above, the SV and Cpk of lost cargo showed a fluctuation and the lowest values of SV and Cpk in September 2013, with SV = 5.07 and Cpk = 1.69.

   Table 24. Sigma value and process capability indices of the damaged cargo

Time	Sigma_value_for_ damaged_cargo (sigma)	Cpk_of_damaged_cargo (Cpk)
Dec 01, 2012	6.00	2.00
Jan 01, 2013	6.00	2.00
Feb 01, 2013	5.91	1.97
Mar 01, 2013	5.70	1.90
Apr 01, 2013	5.80	1.93
May 01, 2013	5.72	1.91
Jun 01, 2013	5.65	1.88
Jul 01, 2013	5.80	1.93
Aug 01, 2013	5.76	1.92
Sep 01, 2013	5.58	1.86
Oct 01, 2013	5.62	1.87
Nov 01, 2013	5.70	1.90

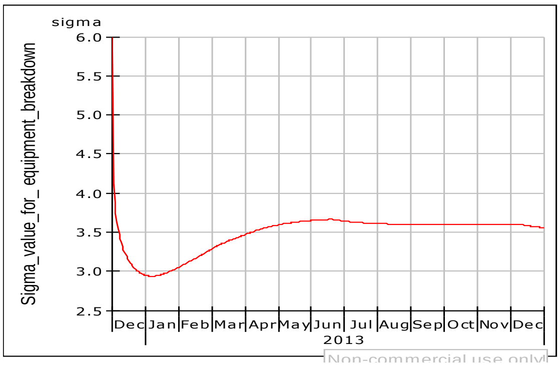


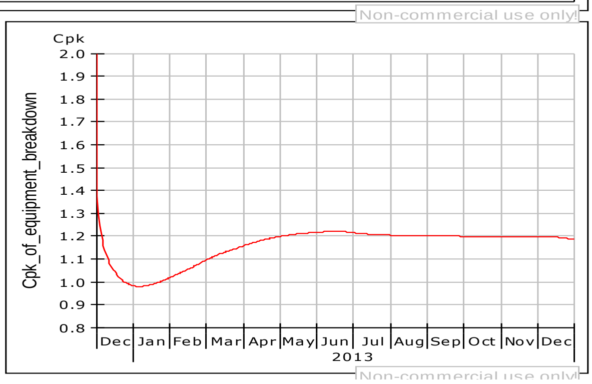


From Table 24 above, the SV and Cpk of damaged cargo showed a fluctuation and the lowest values of SV and Cpk in September 2013, with SV= 5.58 and Cpk = 1.86.

Table 25. Sigma value and process capability indices of the equipment breakdown

Time	Sigma_value_for_ equipment_breakdown (sigma)	Cpk_of_equipment_breakdown (Cpk)
Jan 01, 2013	2.95	0.98
Feb 01, 2013	3.06	1.02
Mar 01, 2013	3.29	1.10
Apr 01, 2013	3.47	1.16
May 01, 2013	3.60	1.20
Jun 01, 2013	3.65	1.22
Jul 01, 2013	3.64	1.21
Aug 01, 2013	3.61	1.20
Sep 01, 2013	3.60	1.20
Oct 01, 2013	3.60	1.20
Nov 01, 2013	3.60	1.20
Dec 01, 2013	3.60	1.20

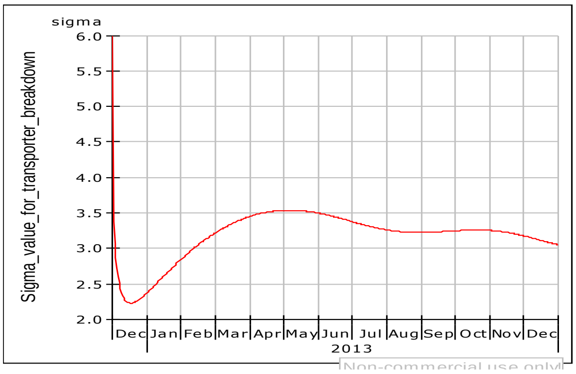


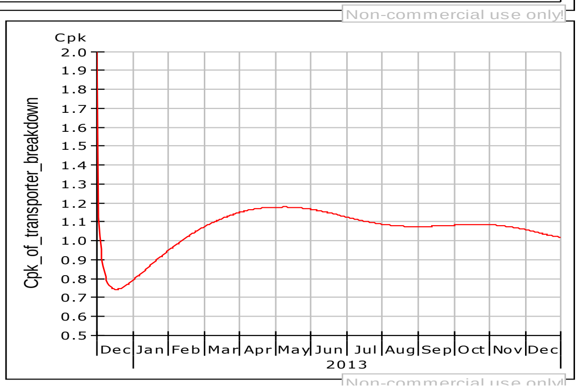


From Table 25 above, the SV and Cpk of equipment breakdown showed an increase and the lowest values of SV and Cpk in January 2013, with SV= 2.95 and Cpk = 0.98.

Table 26. Sigma value and process capability indices (Cpk) of the transporter breakdown

Time	Sigma_value_for_transporter_breakdown (sigma)	Cpk_of_transporter_breakdown (Cpk)
Jan 01, 2013	2.37	0.79
Feb 01, 2013	2.85	0.95
Mar 01, 2013	3.22	1.07
Apr 01, 2013	3.45	1.15
May 01, 2013	3.53	1.18
Jun 01, 2013	3.50	1.17
Jul 01, 2013	3.38	1.13
Aug 01, 2013	3.26	1.09
Sep 01, 2013	3.23	1.08
Oct 01, 2013	3.25	1.08
Nov 01, 2013	3.26	1.09
Dec 01, 2013	3.18	1.06

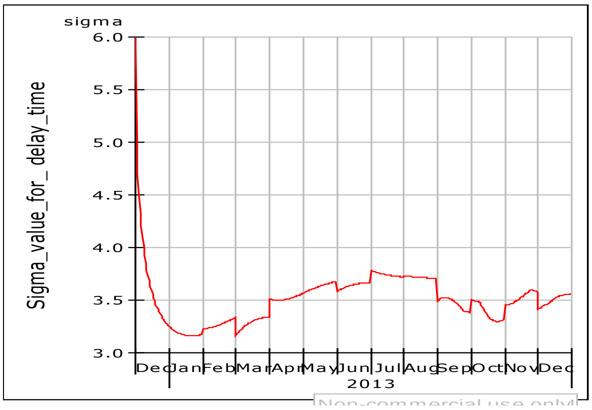


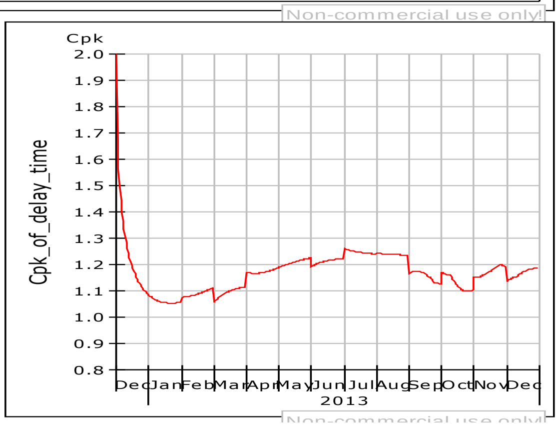


From Table 26 above, the SV and Cpk of transporter breakdown showed an increase until June 2013 then slowly decreased until October 2013, with the lowest values of SV and Cpk in January 2013, with SV= 2.37 and Cpk = 0.79.

Table 27. Sigma value and process capability indices of the delay time

Time	Sigma_value_for_ delay_time (sigma)	Cpk_of_delay_time (Cpk)
Jan 01, 2013	3.25	1.08
Feb 01, 2013	3.23	1.08
Mar 01, 2013	3.17	1.06
Apr 01, 2013	3.52	1.17
May 01, 2013	3.57	1.19
Jun 01, 2013	3.58	1.19
Jul 01, 2013	3.79	1.26
Aug 01, 2013	3.73	1.24
Sep 01, 2013	3.50	1.17
Oct 01, 2013	3.51	1.17
Nov 01, 2013	3.46	1.15
Dec 01, 2013	3.41	1.14





From Table 27 above, the SV and Cpk of delay time showed an increase until July 2013 then slowly decreased until October 2013, with the lowest values of SV and Cpk in March 2013, with SV= 3.17 and Cpk = 1.06.

The behavior of sigma value follows the goal seeking structure to reach the desired value of 6 sigma-level. In general, the sigma values of the lost and damaged cargo were in the 5 sigma-level, which showed that poor quality of cargo is not significant, and the process capability indices above 1.33 determine that the cargo-handling process can meet the customer requirements or specifications. However, the sigma values of the equipment and transporter breakdown and delay time were in the 3-level, which showed that poor quality is significant and needs to be eliminated or reduced, while the process capability indices approaching the minimum level (around 1.0) indicate that the cargo-handling process can meet customer requirements or specifications at the minimum limit.

2. The cost of poor quality (COPQ)

The internal failure cost contributes most of the non-conformance cost. The demurrage cost is the highest cost of the internal failure cost, followed by the repair cost and lost cargo cost. The prevention cost components that have the most effect on the conformance cost. The table and graphic of the COPQ components in detail have been explained in chapter 6.3, the base case of simulation.

Chapter 7

The Policy of Improvement Scenarios and Analysis

Some scenarios for the improvement policy are developed and analyzed to respond to the changes in the system of the port. According to Balance Technology Consulting GmbH (2014), the growth of dry bulk cargo was 5.4% per year in the period 2013–2017. Improvement policy scenarios are proposed to anticipate and respond to this condition. The 5.4% growth is input as the customer order in the stock flow diagram.

7.1 Improvement Policy Scenarios in the Port Operation

In port operation, the scenarios are proposed to reduce or eliminate the vessel waiting time, which is shown by the value of the berth occupancy ratio (BOR). The improvement policy scenarios have been designed to anticipate or respond to the 5.4% annual growth of customer orders. The objective of the improvement scenarios in the port operation is to reduce the vessel waiting time (Tw) with reducing the BOR in appropriate value. The vessel waiting time relates to the operation time as one of the service indicators. Meanwhile, the BOR is one of the utilization indicators. Therefore, reducing the vessel waiting time obviously is part of a trade-off due to the BOR value as an indicator of the berth utilization. These scenarios increase the operation cycle of the crane (Cc) and the lifting capacity of the crane (Lcc). The formulation of the two scenarios is as below:

$$\mathrm{BOR}_{t=i} = \frac{\left(\mathrm{Sv}_{(t0)} + \int_{t0}^{t}\left[\left(\frac{(\mathrm{Svd(s)} - \mathrm{Sv(s)})}{\mathrm{tav}}\right)\right]\mathrm{ds}\right) \times \left(\frac{1}{\mathrm{oct}_{(t=i)} \times \mathrm{ct}_{(t=i)} \times \mathrm{Nb}_{(t=i)}} + \frac{\mathrm{Wv}_{(t=n)}}{\mathrm{Lcc}_{(t=i)} \times \mathrm{Cc}_{(t=i)} \times \mathrm{Nc}_{(t=i)}}\right)}{\mathrm{Bn} \times \mathrm{Wd} \times \mathrm{Wh}};\ \mathrm{i} = 0, 1, 2, 3, .., \mathrm{n} \quad (7.1)$$

$$\mathrm{df}_{t=i} = 1.563 \times 10^{-18} \times e^{(43 \times \mathrm{BOR}_{(t=i)})} + 0.0001014 \times e^{(9.523 \times \mathrm{BOR}_{(t=i)})};\ \mathrm{i} = 0, 1, 2, 3, .., \mathrm{n} \quad (7.2)$$

$$\mathrm{Tw}_{t=i} = \mathrm{Ts}_{t=i} \times \mathrm{df}_{(t=i)}\ ;\ \mathrm{i} = 0, 1, 2, 3, .., \mathrm{n} \quad (7.3)$$

where:

BOR = the berth occupancy ratio,
Sv = the number of unloaded vessels,
Svd = the desired number of unloaded vessels,
Wv = the load per vessel,
Oct = the operation cycles of tugboat
ct = the capacity of tugboat
Nb = the number of tugboats,
Cc = the operation cycles of crane,
Lcc = the lifting capacity of crane,
Nc = the number of cranes,
Tw = the vessel waiting time,
Ts = the vessel service time,
df = delay factor,
Bn = the number of berths,

Wd = the number of days per month,

Wh = the number of working hours per day,

tav = the adjustment time for the arrival rate of vessel.

The improvement scenarios in the port operation are explained in detail as follows:

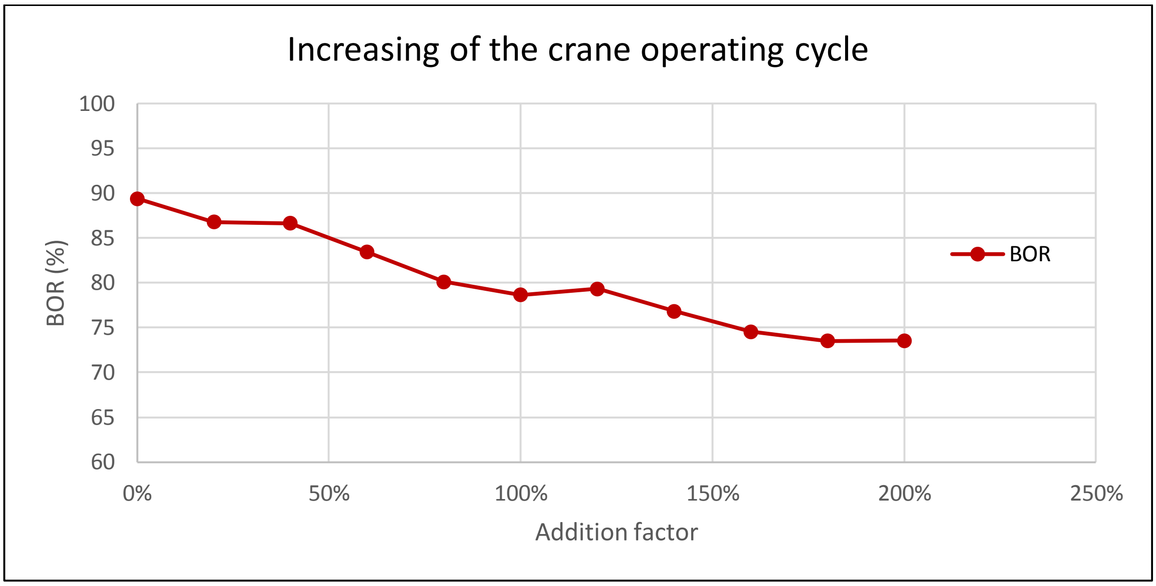
1. **Increasing the operation cycle of the crane**

   The increase has been selected in steps of 20%. The best result from the scenario trial is a 100% increase of the operation cycle of the crane. All the result simulations of increasing the operating cycle of the crane were done by trial, as depicted in Table 28 below:

Table 28. Simulation results by trial of changing the crane operation cycle

The operation cycle of the crane (cycle/day)		Key performance indicators in port operation	
Addition factor	Experiment	BOR (%)	Vessel waiting time (da/vessel)
0 % (315)	Base case	89.4	7.58
20 % (378)	1	86.77 -2.94%	8.68 14.51%
40% (441)	2	86.63 -3.10%	8.27 9.10%
60% (504)	3	83.44 -6.67%	6.22 -17.94%
80% (567)	4	80.13 -10.37%	5.37 -29.16%
100% (630)	5	78.66 -12.01%	4.45 -41.29%
120% (693)	6	79.34 -11.25%	6.20 -18.21%
140% (756)	7	76.83 -14.06%	4.91 -35.22%
160% (819)	8	74.54 -16.62%	3.73 -50.79%
180% (882)	9	73.51 -17.77%	2.92 -61.48%
200% (945)	10	73.55 -17.73%	4.05 -46.57%

The addition factor for increasing the operating cycle of the crane have the effect of decreasing the BOR and the vessel waiting time. The trend of the decreasing BOR and vessel waiting time is described in Figure 75 below:



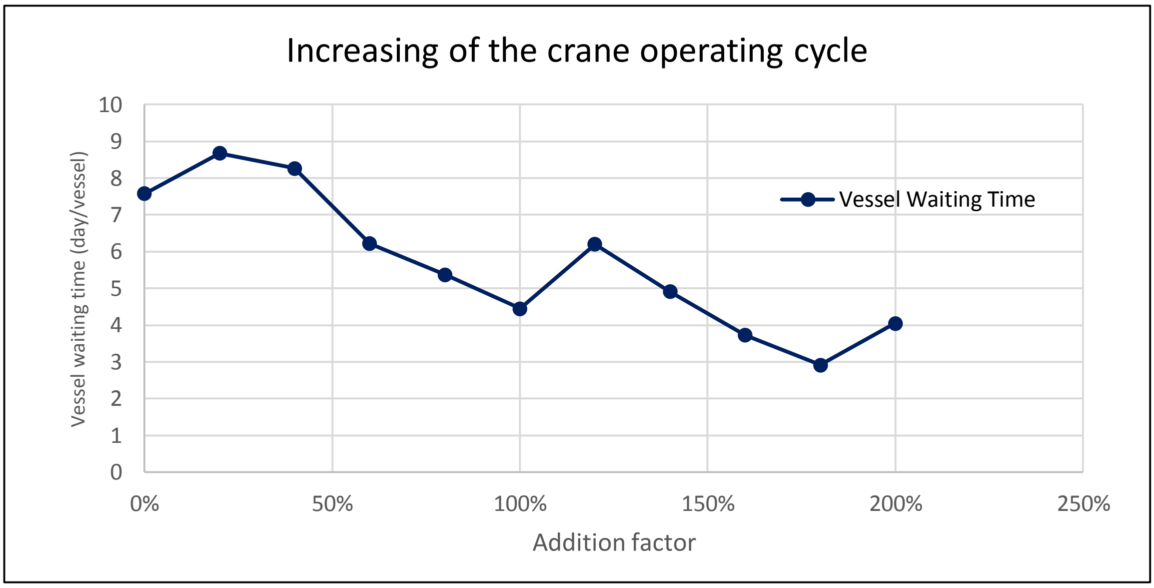


Figure 75. Decreasing the BOR and vessel waiting time by increasing the crane operating cycle

Analysis of Variance (ANOVA) test is conducted to prove whether the model scenario results differ with the different changes of the crane operation cycle. All the result simulations of increasing the operating cycle of the crane are normally distributed. In this scenario, the test is done in relation to the port operation performance, berth occupancy ratio (BOR) and vessel waiting time using two-way ANOVA (α=0.05) with the hypothesis:

H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$, meaning that there are no differences among groups

H_1: at least two groups have differences

where μ_1 to μ_5 is the main value of the scenario output of each port operation performance indicator.

ANOVA is calculated by comparing between the groups variance and the error variance to get the value of F. Also, the F critical value is determined by an F table based on the degree of freedom, df, and degree of confidence, α. The result of the design scenarios are differences significantly when the F value > the F critical, or the p-value ≤ α (0.05), this means H_0 is rejected. The F value are calculated by the formulation below:

$$\mathrm{F} = \frac{\mathrm{MS_T}}{\mathrm{MS_E}} \tag{7.4}$$

$$\mathrm{F_A} = \frac{\mathrm{MS_A}}{\mathrm{MS_E}} \tag{7.5}$$

$$\mathrm{F_B} = \frac{\mathrm{MS_B}}{\mathrm{MS_E}} \tag{7.6}$$

$$\mathrm{MS_T} = \frac{\mathrm{SS_T}}{\mathrm{df_T}} \tag{7.7}$$

$$\mathrm{MS_A} = \frac{\mathrm{SS_A}}{\mathrm{df_A}} \tag{7.8}$$

$$\mathrm{MS_B} = \frac{\mathrm{SS_B}}{\mathrm{df_B}} \tag{7.9}$$

$$\mathrm{MS_E} = \frac{\mathrm{SS_E}}{\mathrm{df_E}} \tag{7.10}$$

$$\mathrm{SS_T} = \sum_i \sum_j (x_{ij} - \overline{x})^2 \tag{7.11}$$

$$\mathrm{SS_A} = c \sum_i (\overline{x}_i - \overline{x})^2 \tag{7.12}$$

$$\mathrm{SS_B} = r \sum_j (\overline{x}_j - \overline{x})^2 \tag{7.13}$$

$$\mathrm{SS_E} = \sum_i \sum_j (x_{ij} - \overline{x}_i - \overline{x}_j + \overline{x})^2 \tag{7.14}$$

$$\mathrm{df_T} = n - 1 \tag{7.15}$$

$$\mathrm{df_A} = r - 1 \tag{7.16}$$

$$\mathrm{df_B} = c - 1 \tag{7.17}$$

$$\mathrm{df_E} = (r - 1)(c - 1) \tag{7.18}$$

Where:

$\mathrm{F_A}$ = F value for the rows (factor A) with the index i

$\mathrm{F_B}$ = F value for the columns (factor B) with the index j

$\mathrm{MS_T}$= Mean square between treatment

$\mathrm{MS_A}$= Mean square between treatment for the rows (factor A)

$\mathrm{MS_B}$= Mean square between treatment for the columns (factor B)

$\mathrm{MS_E}$= Mean square due to error

$\mathrm{SS_T}$ = Sum square between treatment

$\mathrm{SS_A}$ = Sum square between treatment for the rows (factor A)

$\mathrm{SS_B}$ = Sum square between treatment for the columns (factor B)

SS_E = Sum square due to error

df_T = degree of freedom for variance between sample

df_A = degree of freedom for variance between sample for the rows (factor A) with r levels

df_B = degree of freedom for variance between sample for the columns (factor B) with c levels

df_E = degree of freedom for variance within sample

The results of ANOVA for this hypothesis are shown in Table 29 below.

Table 29. Output of ANOVA for changing the crane operation cycle

Anova: Two-Factor Without Replication

SUMMARY	Count	Sum	Average	Variance
Base case	2	96.98	48.49	3347.26
1	2	95.45	47.73	3049.02
2	2	94.90	47.45	3070.14
3	2	89.66	44.83	2981.46
4	2	85.50	42.75	2794.53
5	2	83.11	41.56	2753.56
6	2	85.54	42.77	2674.73
7	2	81.74	40.87	2586.24
8	2	78.27	39.14	2507.03
9	2	76.43	38.22	2491.47
10	2	77.60	38.80	2415.13
BOR	11	882.80	80.25	31.51
Vessel waiting time	11	62.38	5.67	3.62

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Rows	275.63	10	27.56	3.64	0.03	2.98
Columns	30594.95	1	30594.95	4045.52	0.00	4.96
Error	75.63	10	7.56			
Total	30946.21	21				

As a conclusion, based on the ANOVA test results, the F value rows (3.64) > the F critical value (2.98) or the P-value rows (0.03) ≤ α (0.05), this means H_0 is rejected; in other word that there are differences regarding reducing the BOR and vessel waiting time based on the increase factors of the crane operation cycle. On the other hand, based on the simulation result of the scenario, the higher the crane operation cycle, the lower the BOR and vessel waiting time. Increase of the crane operation cycle should be considered to reduce both the port operation performance indicators. Based on the simulation, the increase of the crane operation cycle should be a maximum 100%, which will have the effect of a 12.01% reduction of the BOR and 41.29% of the vessel waiting time.

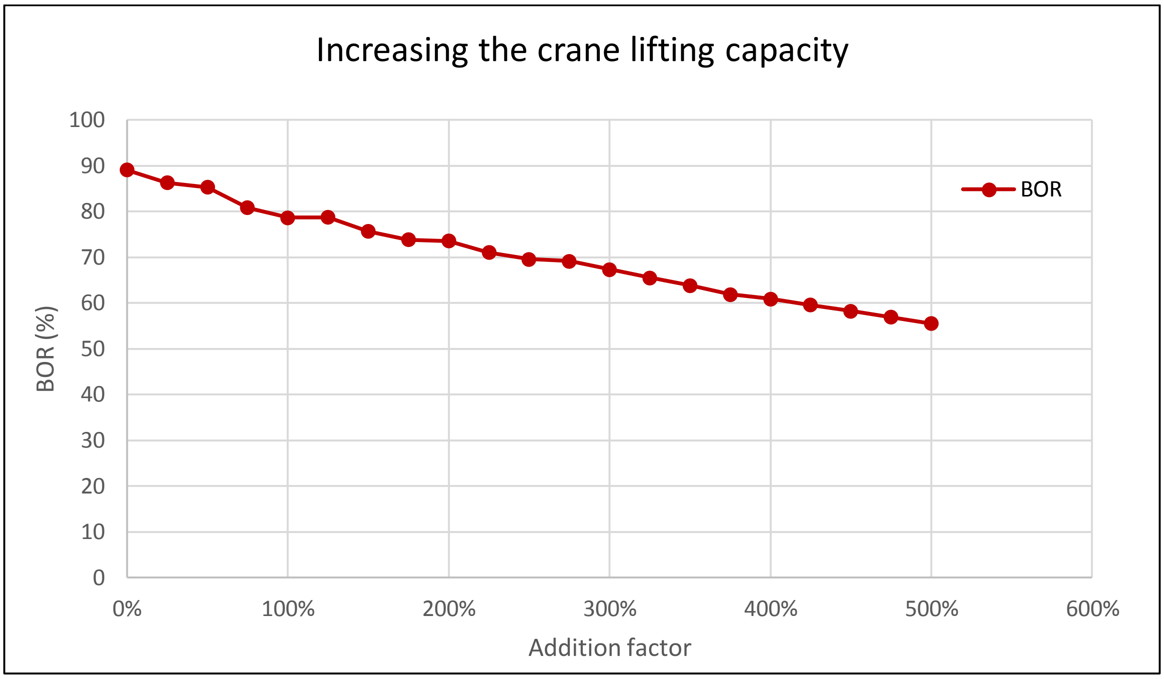
2. Increasing the lifting capacity of the crane

The increase has been selected in steps of 25%. The best result from the scenario trial is a 500% increase of the lifting capacity of the crane. The addition factor for increasing the lifting capacity of the crane have the effect of decreasing the BOR and the vessel waiting time. All the result simulations of increasing the lifting capacity of the crane have been conducted by trial, as depicted in Table 30 below:

Table 30. Simulation results by trial of changing the crane lifting capacity

Crane lifting capacity (tons)		Key performance indicators in port operation	
Addition factor	Experiment	BOR (%)	Vessel waiting time (da/vessel)
0 % (14)	Base case	89.05	7.58
25 % (17.5)	1	86.26 -3.13%	8.03 5.94%
50 % (21)	2	85.32 -4.19%	8.41 10.95
75 % (24.5)	3	80.84 -9.22%	5.41 -28.63%
100 % (28)	4	78.66 -11.67%	4.45 -41.29%
125 % (31.5)	5	78.74 -11.58%	5.97 -21.24
150 % (35)	6	75.67 -15.03%	4.36 -42.48%
175 % (38.5)	7	73.81 -17.11%	2.87 -62.14%
200% (42)	8	73.55 17.41%	4.05 -46.57%
225 % (45.5)	9	71.00 -20.27	3.52 -53.56
250 % (49)	10	69.53 -21.92%	3.48 -54.09%
275 % (52.5)	11	69.14 -22.36%	4.54 -40.11%
300% (56)	12	67.31 -24.41%	3.44 -54.62%
325 % (59.5)	13	65.48 -26.47%	2.87 -62.14%
350 % (63)	14	63.81 -28.34%	2.69 -64.51%
375% (67.5)	15	61.87 -30.52%	2.51 -66.89%
400% (70)	16	60.89 -31.62%	2.42 -68.07%
425 % (73.5)	17	59.55 -33.13%	2.12 -72.03%
450 % (77)	18	58.24 -34.60%	1.78 -76.52%
475% (80.5)	19	56.87 -36.14%	1.23 -83.77%
500% (84)	20	55.48 -37.70%	0.81 -89.31%

The addition factor for increasing the lifting capacity of the crane have the effect of decreasing the BOR and the vessel waiting time. The trend of reducing the BOR and vessel waiting time is described in Figure 76 below:



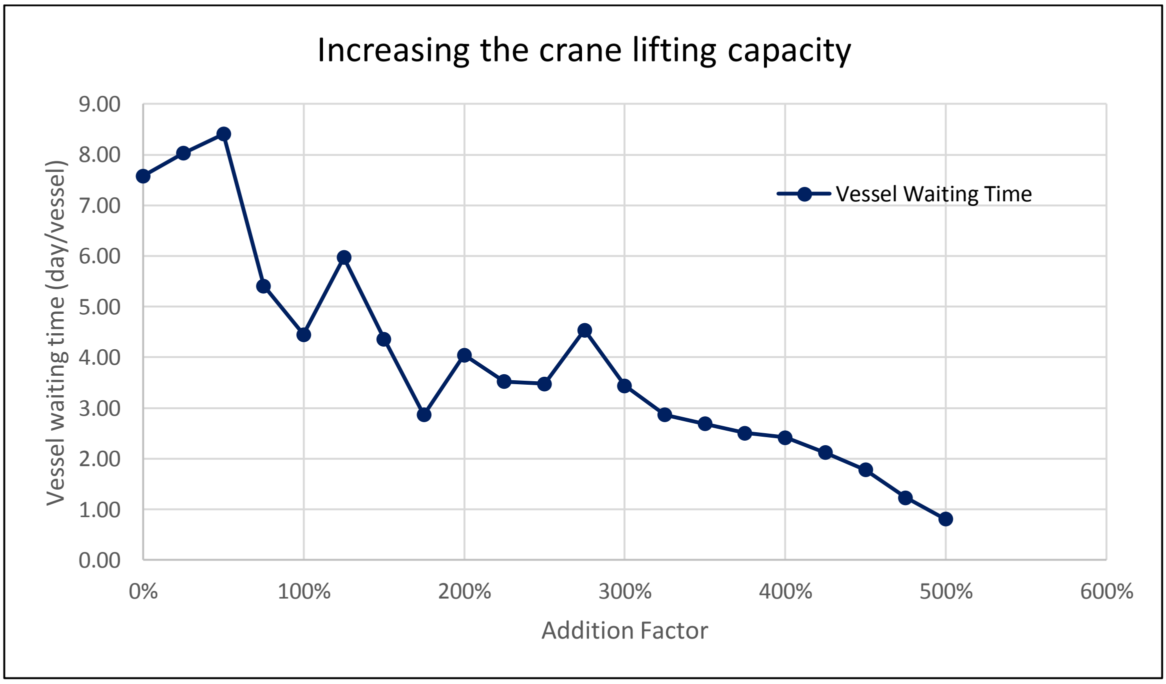


Figure 76. Decreasing the BOR and vessel waiting time by increasing the crane lifting capacity

An ANOVA test is also done to prove whether the model scenario results differ with each change of the crane lifting capacity. All the result simulations of increasing the crane lifting capacity are normally distributed. In this scenario, the test is performed in relation to the port operation performance, berth occupancy ratio (BOR) and vessel waiting time using two-way ANOVA (α=0.05).

The results of ANOVA for this hypothesis can be observed in Table 31 below:

Table 31. Output of ANOVA for changing the crane lifting capacity

Anova: Two-Factor Without Replication

SUMMARY	Count	Sum	Average	Variance		
Base Case	2	96.63	48.32	3318.68		
1	2	94.29	47.15	3059.97		
2	2	93.73	46.87	2957.57		
3	2	86.25	43.13	2844.84		
4	2	83.11	41.56	2753.56		
5	2	84.71	42.36	2647.74		
6	2	80.03	40.02	2542.56		
7	2	76.68	38.34	2516.24		
8	2	77.60	38.80	2415.13		
9	2	74.52	37.26	2276.78		
10	2	73.01	36.51	2181.30		
11	2	73.68	36.84	2086.58		
12	2	70.75	35.38	2039.69		
13	2	68.35	34.18	1960.01		
14	2	66.50	33.25	1867.83		
15	2	64.38	32.19	1761.80		
16	2	63.31	31.66	1709.37		
17	2	61.67	30.84	1649.10		
18	2	60.02	30.01	1593.87		
19	2	58.10	29.05	1547.90		
20	2	56.29	28.15	1494.40		
BOR	21	1481.07	70.53	101.60		
Vessel Waiting Time	21	82.54	3.93	4.55		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Rows	1466.88	20	73.34	2.24	0.04	2.12
Columns	46568.72	1	46568.72	1419.35	0.00	4.35
Error	656.20	20	32.81			
Total	48691.80	41				

As a conclusion, based on the ANOVA test results, the F value rows (2.24) > the F critical value (2.12) or the P-value rows (0.04) ≤ α (0.05), this means H_0 is rejected; in other word that there are differences regarding reducing the BOR and vessel waiting time based on the increase factors of the crane lifting capacity. On the other hand, based on the simulation result of the scenario, the greater the crane lifting capacity, the less the BOR and vessel waiting time. The increase of the lifting capacity should be considered to reduce both the port operation performance indicators. Based on the simulation, the increase of the crane lifting capacity should be a maximum of 500%, which will have the effect of a 37.70% reduction of the BOR and 89.31% of the vessel waiting time.

7.2 Improvement Policy Scenarios in the Port Quality Level

The objective of the improvement policy scenarios in the port quality level is to reduce the internal failure cost, which involves the repair cost, demurrage cost, and lost cargo cost. The formulation for all scenarios is depicted below:

$$\mathrm{RC\ (t) = RC(t_0) +} \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{\mathrm{TRC_{transporter}(s) + TRC_{equipment\ (S)}}}{\mathrm{AT\ rc}}\right] \mathrm{ds} \tag{7.19}$$

$$\mathrm{TRC_{transporter} = TBT\ x\ RCT} \tag{7.20}$$

where RC represents the repair cost (US$), $TRC_{transporter}$ represents the total repair cost of the transporter (US$), which comprises the number of transporter breakdown items (TBT) times the repair cost per transporter (RCT), $TRC_{equipment}$ represents the total repair cost of equipment (US$), and ATrc represents the adjustment time for the repair cost rate (month). The number of transporter breakdown items (TBT) is given below:

$$\mathrm{TBT\ (t) = TBT\,(t_0) +} \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{168.3\ \mathrm{x}\ e^{(-1.01\ \mathrm{x\ PC\ effect(s)})} + 226.4\ \mathrm{x}\ \mathrm{e}^{(-0.2798\ \mathrm{x\ PC\ effect(s)})}}{\mathrm{ta_{tb}}}\right] \mathrm{ds} \tag{7.21}$$

$$\mathrm{PC\ Effect} = \frac{\mathrm{TMC(t_0)} + \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{\mathrm{NTM(s)\ x\ MCT}}{\mathrm{ta_{tmc}}}\right] \mathrm{ds}}{\mathrm{PC}}\ \mathrm{x\ 100\ \%} \tag{7.22}$$

where PC effect is an effect of prevention cost to the repair cost (%). This variable describes the causal relation between the transporter maintenance cost and the number of transporter breakdowns. TMC is transporter maintenance cost (US$), NTM is the number of transporter maintenance items (item), MCT is the maintenance cost for transporter per item (US$), PC is the prevention cost (US$), $\mathrm{ta_{tmc}}$ represents the adjustment time for the rate of the transporter maintenance cost (month), and $\mathrm{ta_{tb}}$ represents the adjustment time for the rate of the number of transporter breakdown items (month). Meanwhile, the equation of RC and TBT for the effect of this scenario on the demurrage cost is depicted below:

$$\mathrm{DC\ (t) = DC(t_0) +} \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{\mathrm{(DM+DR)(s) x\ DCH}}{\mathrm{ta_{dc}}}\right] \mathrm{ds} \tag{7.23}$$

$$\mathrm{DR\ (t) = DR(t_0) +} \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{\mathrm{ERT(s) + TRT(s)}}{\mathrm{ta_{dr}}}\right] \mathrm{ds} \tag{7.24}$$

$$\mathrm{DM\ (t) = DM(t_0) +} \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{\mathrm{EMT(s) + TMT(s)}}{\mathrm{ta_{dm}}}\Big)\right] \mathrm{ds} \tag{7.25}$$

$$\mathrm{TRT} = \mathrm{TBT\ X\ RTT} \tag{7.26}$$

$$\mathrm{TMT} = \mathrm{NTM\ X\ MTT} \tag{7.27}$$

where,

DC = the demurrage cost (US$),

DM = the delay due to maintenance (hours),

DR = the delay due to repair (hours),

DCH = the demurrage cost per hour (US$/hour),

ERT = the equipment repair time (hours),

TRT = the transporter repair time (hours),

TBT = the number of transporter breakdown items (items),

RTT = the repair time per transporter item (hours),

EMT = the equipment maintenance time (hours),

TMT = the transporter maintenance time (hours),

NTM = the number of transporter maintenance items (items),

MTT = the maintenance time per transporter item (hours),

$\mathrm{ta_{dc}}$ = the adjustment time for the demurrage cost rate (month),

$\mathrm{ta_{dr}}$ = the adjustment time for the delay due to repair (month),

$\mathrm{ta_{dm}}$ = the adjustment time for the delay due to maintenance (month).

Another scenario involves modifying the percentage of increase, which directly affects the safety and security cost as well as the cargo inspection cost. This general scenario is defined in the following equation:

$$\mathrm{LCC\ (t)} = \mathrm{LCC(t_0)} + \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{\mathrm{LC(s)\ x\ CLC}}{\mathrm{ta_{lcc}}}\right] \mathrm{ds} \tag{7.28}$$

$$\mathrm{LC\ (t)} = \mathrm{LC\ (t_0)} + \int_{\mathrm{to}}^{\mathrm{t}} \left[\frac{-8.488\mathrm{x}10^{-05}\ \mathrm{x}\ \mathrm{e}^{(0.1736\ \mathrm{x\ ACPC\ effect(s)})} + 0.1001\ \mathrm{x}\ \mathrm{e}^{(-0.09248\ \mathrm{x\ ACPC\ effect(s)})}}{\mathrm{ta_{lc}}}\right] \mathrm{ds} \tag{7.29}$$

$$\mathrm{ACPC\ effect} = \left[\frac{\mathrm{SSC}}{\mathrm{PC}} + \frac{\mathrm{NI\ x\ CI\ x\ Sv}}{\mathrm{AC}}\right] \mathrm{x}\ 100\ \% \tag{7.30}$$

Where,

LCC = the lost cargo cost (US$),

LC = the amount of lost cargo (tons),

CLC = the cost per lost cargo (US$/ton),

SSC = the safety & security cost (US$),

PC = the prevention cost (US$),

NI = the number of inspectors (person/vessel),

CI = the cost per inspector (US$),

AC = the appraisal cost (US$),

Sv = the number of unloaded vessels (vessel),

ta_{lcc} = the adjustment time for the lost cargo cost rate (month),

ta_{lc} = the adjustment time for the amount of lost cargo rate (month).

ACPC effect is an effect of prevention and appraisal cost to the lost cargo cost (%). This variable describes the causal relation between the safety & security cost and the number of inspectors, and the amount of lost cargo.

The trials of reducing the demurrage cost, repair cost, and lost cargo cost are explained in detail below:

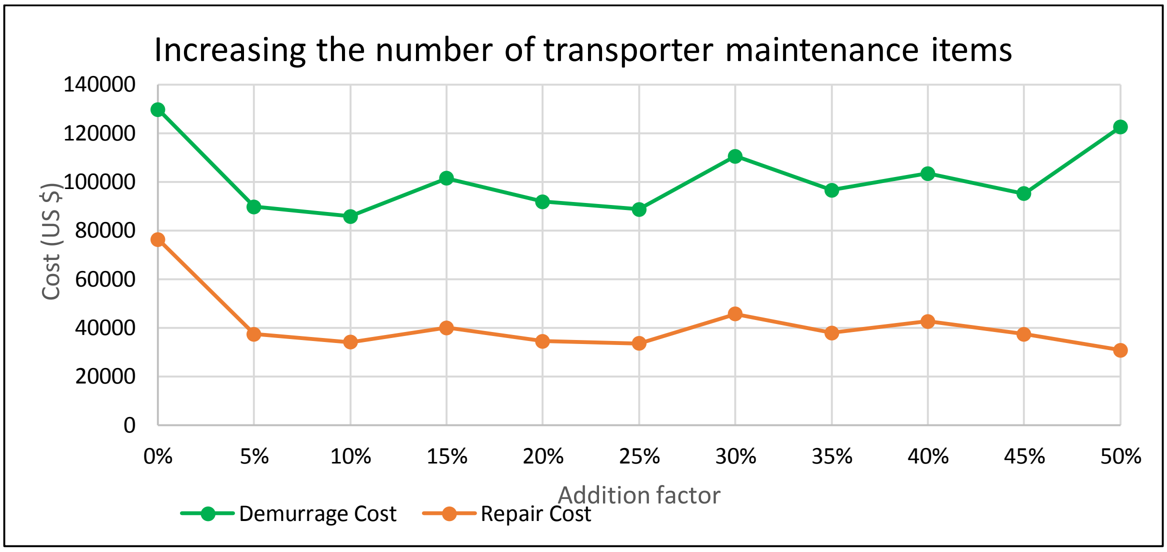
1. **Reducing demurrage cost (DC) and repair cost (RC)**

   A trial with different percentage increases of the number of transporter maintenance items, which can decrease the demurrage and repair costs, is depicted in Table 32 below:

Table 32. Trial with various rates of increase of transporter maintenance items to reduce the demurrage and repair costs

Number of transporter maintenance items		Cost Components (USD)				
Addition factor	Experiment	Demurrage cost	Repair cost	Opportunity cost	Internal failure cost	Cost of poor quality (COPQ)
0% (277)	Base case	129,700	76,349	313,898	408,369	1,158,336
5% (291)	1	89,685 -31%	37,323 -51%	304,006 -3%	352,605 -14%	1,095,305 -5%
10% (305)	2	85,779 -34%	34,019 -55%	311,078 -1%	354,672 -13%	1,099,915 -5%
15% (319)	3	101,464 -22%	40,044 -48%	316,755 1%	369,238 -10%	1,123,259 -3%
20% (332)	4	91,875 -29%	34,465 -55%	322,475 3%	366,117 -10%	1,121,374 -3%
25% (346)	5	88,677 -32%	33,520 -56%	305,443 -3%	348,209 -15%	1,090,547 -6%
30% (360)	6	110,477 -15%	45,625 -40%	304,053 -3%	364,760 -11%	1,112,072 -4%
35% (374)	7	96,600 -26%	37,930 -50%	301,926 -4%	351,693 -14%	1,093,759 -6%
40% (388)	8	103,462 -20%	42,622 -44%	307,501 -2%	361,402 -12%	1,104,608 -5%
45% (402)	9	95,138 -27%	37,348 -51%	301,465 -4%	348,484 -15%	1,086,575 -6%
50% (416)	10	122,516 -6%	30,825 -60%	356,508 14%	403,225 -1%	1,192,971 3%

The addition factor of the number of transporter maintenance items affects the reduction of the demurrage and repair costs. Also, the addition factor can decrease to some degree the internal failure cost, opportunity cost and the cost of poor quality. The trend of reducing the cost types according to the different numbers of transporter maintenance items is described in Figure 77 below:



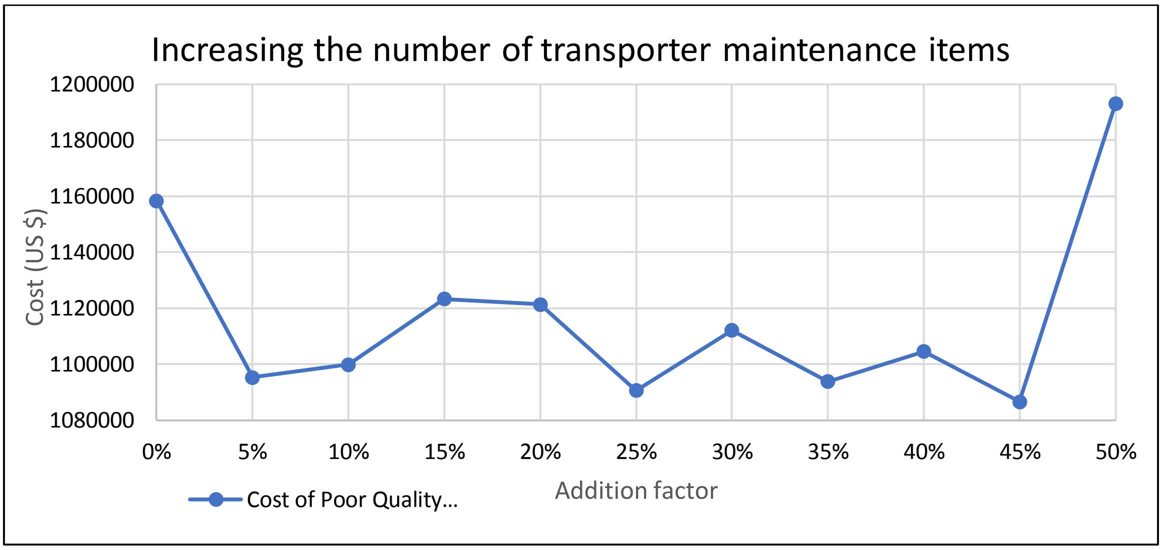


Figure 77. Reducing the cost types by varying the number of transporter maintenance items

An ANOVA test is also done to prove whether the model scenario results differ for each cost structure. All the result simulations of the addition factor of the number of transporter maintenance items are normally distributed. In this scenario, the test is done for cost-related factors such as the demurrage cost, repair cost, internal failure cost, opportunity cost, and COPQ using two-way ANOVA (α=0.05).

The results of ANOVA for this hypothesis can be observed in Table 33 below:

Table 33. Output of ANOVA for changing the number of transporter maintenance items

Anova: two-factor without replication

SUMMARY	Count	Sum	Average	Variance		
Base case	5	2086652	417330	1.90.E+11		
1	5	1878924	375785	1.80.E+11		
2	5	1885463	377093	1.82.E+11		
3	5	1950760	390152	1.87.E+11		
4	5	1936306	387261	1.89.E+11		
5	5	1866423	373285	1.79.E+11		
6	5	1936987	387397	1.82.E+11		
7	5	1881908	376382	1.78.E+11		
8	5	1919595	383919	1.80.E+11		
9	5	1869010	373802	1.76.E+11		
10	5	2106045	421209	2.10.E+11		
Demurrage cost	11	1115373	101398	202953312		
Repair cost	11	450070	40915	156161256		
Opportunity cost	11	3445108	313192	250489603		
Internal failure cost	11	4028774	366252	434908057		
Cost of poor quality	11	12278748	1116250	1063694947		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Rows	1.40E+10	10	1.40E+09	7.95	7.18E-07	2.08
Columns	8.13E+12	4	2.03E+12	11518.12	1.22E-60	2.61
Error	7.06E+09	40	1.76E+08			
Total	8.15E+12	54				

As a conclusion, based on the ANOVA test results, the F value rows (7.95) > the F critical value (2.08) or the P-value rows (7.18E-07) ≤ α (0.05), this means H_0 is rejected; in other word that there are differences regarding reducing the cost types based on the increase factors of the number of transporter maintenance items. On the other hand, based on the simulation result of the scenario, the more the number of transporter maintenance items, the less the demurrage and repair cost. Increasing the number of transporter maintenance items should be considered to reduce both the cost components. Based on the simulation, the increase of the number of transporter maintenance items should be a maximum of 45%, otherwise the COPQ will increase slowly. The best solution of the scenario trial is with a 25% increase of the number of transporter maintenance items, which has the effect of a 32% reduction of the demurrage cost and 56% of the repair cost. The COPQ will increase because of the increasing rate of other costs of poor quality components such as the prevention and appraisal costs. Also, the internal failure cost will increase because of the development of other internal failure cost components such as the lost cargo cost and damaged cargo cost.

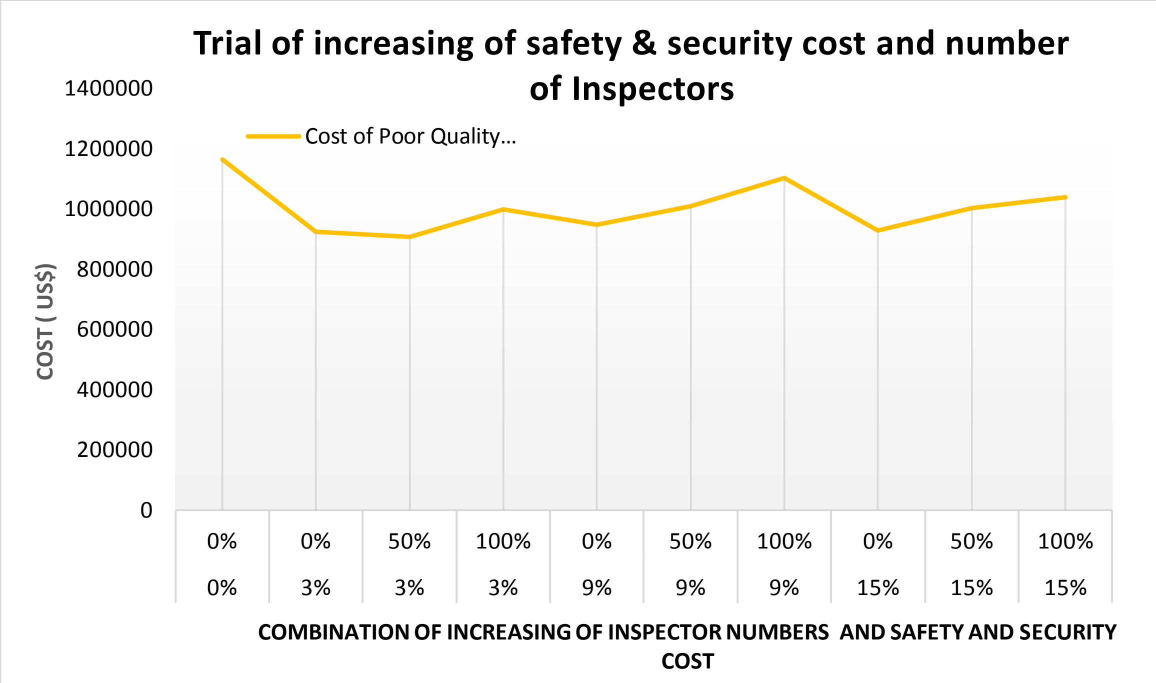
2. **Decreasing the lost cargo cost (LCC)**

A trial was conducted with different percentages of addition to the safety and security cost and the number of inspectors per vessel to decrease the lost cargo cost, as shown in Table 34 below:

Table 34. Trial with various rates of addition of safety and security cost and inspector numbers

Combination of adding factor			Cost Components (USD)			
% Addition for safety and security cost	% Addition for inspection numbers	Experiment	Lost cargo cost	Opportunity cost	Internal failure cost	Cost of poor quality (COPQ)
0% ($577)	0% (10)	Base case	188,114	414,772	314,733	1,163,964
3% ($594)	0% (10)	1	75,269 -60%	271,057 -35%	180,739 -43%	924,504 -21%
3% ($594)	50% (15)	2	61,166 -67%	236,729 -43%	155,447 -51%	907,903 -22%
3% ($594)	100% (20)	3	54,775 -71%	239,264 -42%	154,092 -51%	999,947 -14%
9% ($629)	0% (10)	4	69,770 -63%	290,641 -30%	188,908 -40%	947,906 -19%
9% ($629)	50% (15)	5	61,015 -68%	302,433 -27%	190,460 -39%	1,009,985 -13%
9% ($629)	100% (20)	6	61,682 -67%	301,456 -27%	189,607 -40%	1,103,163 -5%
15% ($664)	0% (10)	7	64,966 -65%	276,874 -33%	179,211 -43%	929,471 -20%
15% ($664)	50% (15)	8	63,346 -66%	295,598 -29%	187,019 -41%	1,004,109 -14%
15% ($664)	100% (20)	9	52,436 -72%	262,311 -37%	164,892 -48%	1,039,735 -11%

The addition factor of the safety and security cost, and inspector numbers has the effect of reducing the lost cargo cost. Also, the increase factor can reduce to some degree the internal failure cost, opportunity cost and the cost of poor quality. The trend of reducing the cost types with various rates of the safety and security cost and inspector numbers is shown in Figure 78 below:



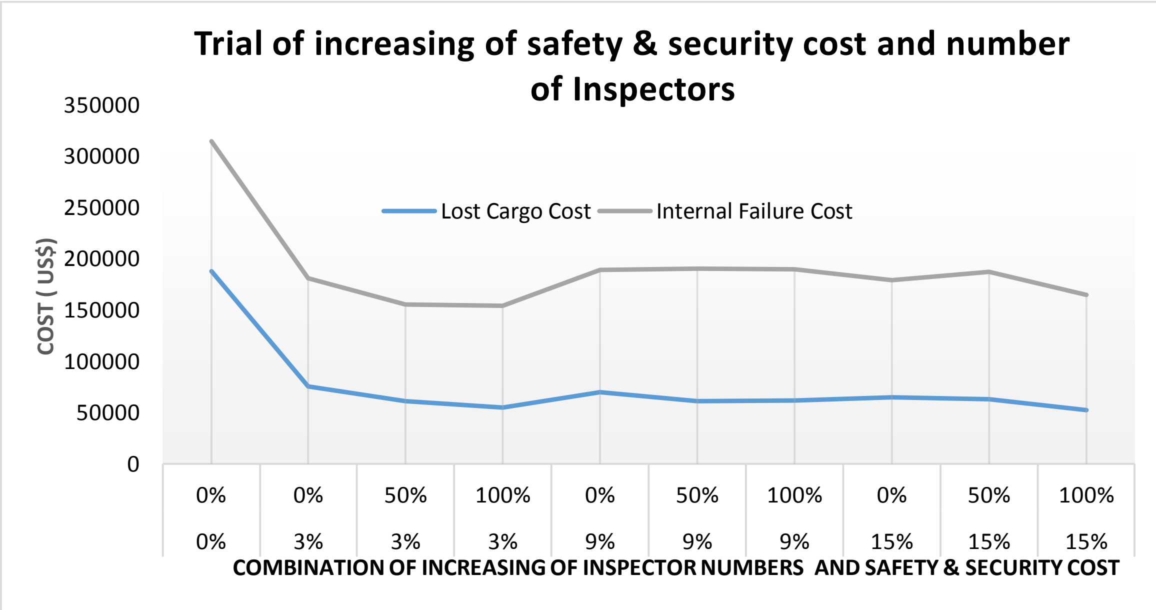


Figure 78. Reducing the cost types with various rates of the safety and security cost and inspector numbers

An ANOVA test is also done to prove whether the model scenario results find wide differences among the results of each cost structure. All the result simulations of the addition factor of the safety and security cost, and inspector numbers are normally distributed. In this scenario, the test is done for cost-related factors such as the lost cargo cost, internal failure cost, opportunity cost, and COPQ using two-way ANOVA (α=0.05). The results of ANOVA for this hypothesis can be observed in Table 35 below:

Table 35. Output of ANOVA for increasing the safety & service cost and inspector numbers

Anova: two-factor without replication

SUMMARY	Count	Sum	Average	Variance		
Base Case	4	2081583	520396	1.93E+11		
1	4	1451569	362892	1.47E+11		
2	4	1361245	340311	1.48E+11		
3	4	1448078	362020	1.87E+11		
4	4	1497225	374306	1.54E+11		
5	4	1563893	390973	1.80E+11		
6	4	1655908	413977	2.21E+11		
7	4	1450522	362631	1.50E+11		
8	4	1550072	387518	1.78E+11		
9	4	1519374	379844	2.01E+11		
Lost Cargo Cost	10	752539	75254	1.62E+09		
Opportunity Cost	10	2891135	289114	2.51E+09		
Internal Failure Cost	10	1905108	190511	2.10E+09		
Cost of Poor Quality (COPQ)	10	1E+07	1003069	6.78E+09		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Rows	9.07E+10	9	1.01E+10	10.33	1.05E-06	2.25
Columns	5.25E+12	3	1.75E+12	1793.67	3.60E-31	2.96
Error	2.63E+10	27	9.75E+08			
Total	5.37E+12	39				

As a conclusion, based on the ANOVA test results, the F value rows (10.33) > the F critical value (2.25) or the P-value rows (1.05E-06) ≤ α (0.05), this means H_0 is rejected; in other word that there are differences regarding reducing cost types based on the combined increase factors of the safety and security cost, and inspector numbers. Furthermore, based on the simulation result, a greater safety and security cost and number of inspectors can lead to a reduction of the lost cargo cost. However, a greater reduction will indirectly affect the other cost components, so that the internal failure cost, opportunity cost and cost of poor quality are not significantly minimized. From the scenario trials shown in Table 33, as an effective combination for reducing the lost cargo and other material costs, the company is advised to add only 3% to the safety and security cost and add 50% to the number of inspectors per vessel, which will have the effect of a 67% reduction in the lost cargo cost.

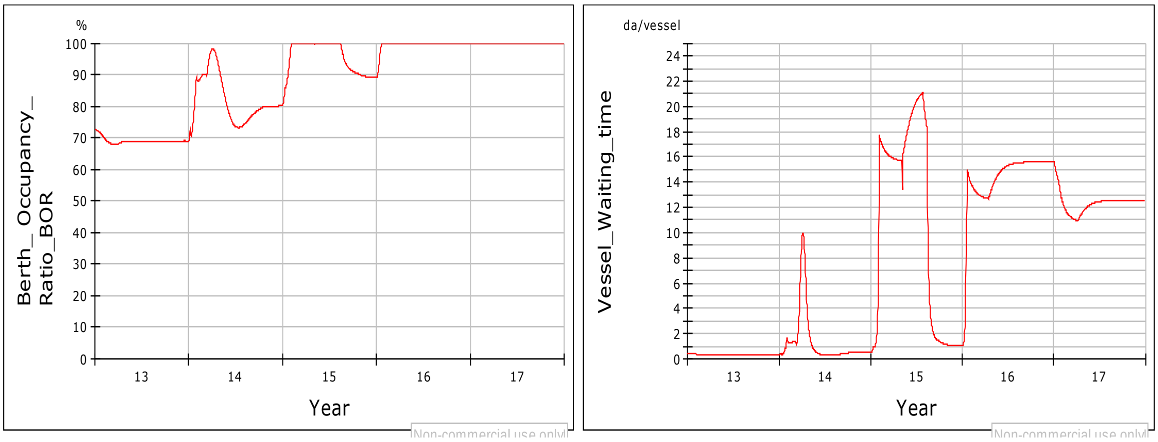
7.3 Improvement Policy Scenarios for the Six Sigma Model

The improvement policies have been formulated by integrating all the trials in the port operation and the port quality level as follows:

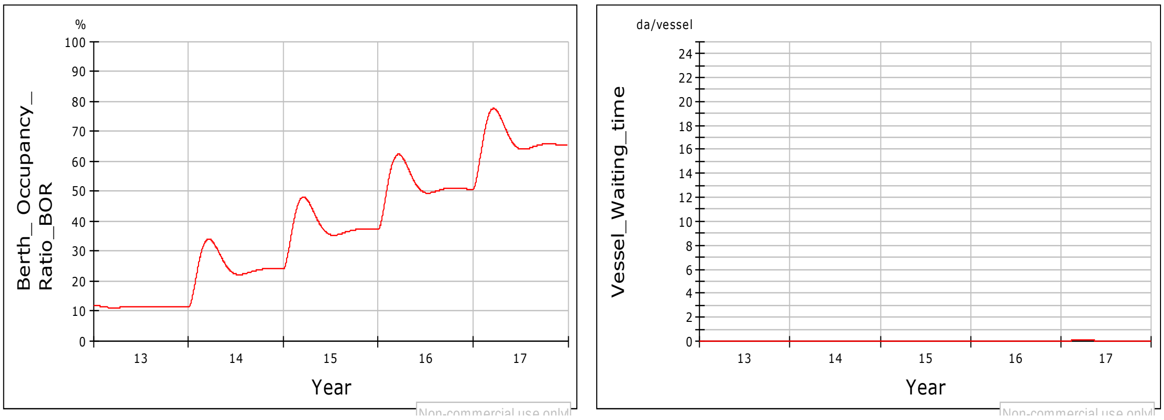
1. Decreasing the berth occupancy ratio (BOR) and the vessel waiting time (Tw).
   The improvement policy scenarios focus to reduce the vessel waiting time with the value of BOR as an indicator. The vessel waiting time relates to the operation time as one of the service indicators. Meanwhile, the BOR is one of the utilization indicators. Therefore, reducing the vessel waiting time obviously is part of a trade-off due to the BOR value as an indicator of the berth utilization. The option of scenarios depends on the decision makers. These improvement scenarios show the behavior of reduction of vessel waiting time with the reduction of the BOR as an indicator. Therefore, the better solution based on trial is with a 100% increase of the crane operation cycle and 500% increase of the crane lifting capacity.
2. Decreasing the demurrage cost (DC) and repair cost (RC).
   The improvement policy scenarios focus to reduce the repair cost and the demurrage cost simultaneously. The reduction of the repair cost has the effect of reducing the demurrage cost. Increasing of the number of transport maintenance items has the effect of reducing the repair cost, but it will increase the demurrage cost because delay time due to maintenance. Therefore, the better solution based on the trial is with a 25% increase of the number of transporter maintenance items.
3. Reducing the lost cargo cost (LCC).
   The improvement policy scenarios focus to reduce the lost cargo cost with the safety and security cost and the inspector numbers as the control variables. The increasing of the safety and security cost and the inspector numbers are trade off because it will increase the appraisal cost. The high appraisal cost will contribute to the high cost of poor quality. Therefore, the better solution based on the trial is with a 3% increase of the safety and security cost and a 50% increase of inspector numbers.

The improvement scenarios taken in response to the growth and the simulation results are explained in detail below:

1. **The port operation**
   These improvement scenarios focus on decreasing the berth occupancy ratio (BOR) and the vessel waiting time. The Figure 79 below shows the behavior of the BOR and vessel waiting time before and after improvement by simulation:



a) Before



b) After

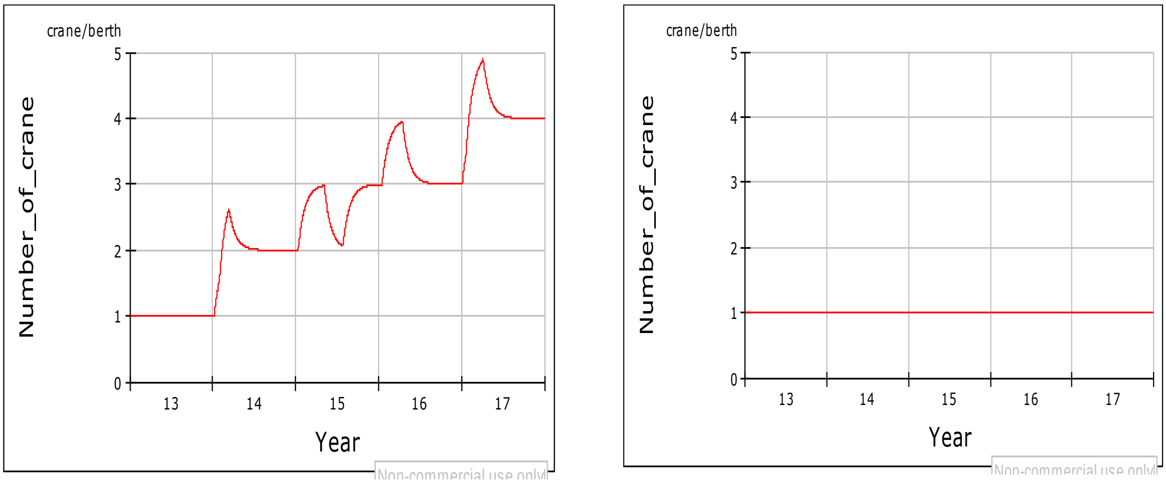
Figure 79. Trend of the BOR and the vessel waiting time: a) before; and b) after improvement by simulation

From Figure 79, the behavior of the BOR before improvement shows the value of BOR is more than 70 % and the vessel waiting time is more than 20 days/vessel. After improvement, the value of BOR is less than 80 % and the vessel waiting time is closer to zero. Decision makers will determine the value of the BOR that will be taken for the policy of improvement scenarios. The options of the policy relate to the decreasing of the vessel waiting time. The simulation results for the average value before and after the improvement policies are compared as depicted in Table 36 below:

Table 36. Simulation results of the BOR and vessel waiting time before and after improvement policies

No	Key performances indicators of the port operation	Before	After
1	Berth occupancy ratio (BOR)	89.33%	38.25%
2	Vessel waiting time	7.71 day/vessel	0.01 day/vessel

The Figure 80 below shows the behavior of the number of cranes before and after improvement by simulation.



a) b)

Figure 80. Trend of the number of cranes: a) before; and b) after improvement by simulation

The operation variable for the number of cranes is changed before and after improvement. The number of cranes reaches a maximum value of 4.86 crane/berths before improvement and reaches a maximum value of 1.00 crane/berths after improvement. From Figure 80 above, it shows that the increasing of the crane operation cycle and the crane lifting capacity have the effect of the reducing the number of cranes. In other simulation results, the operation variables and the cargo throughput before and after the improvement scenarios, as depicted in Table 37 below:

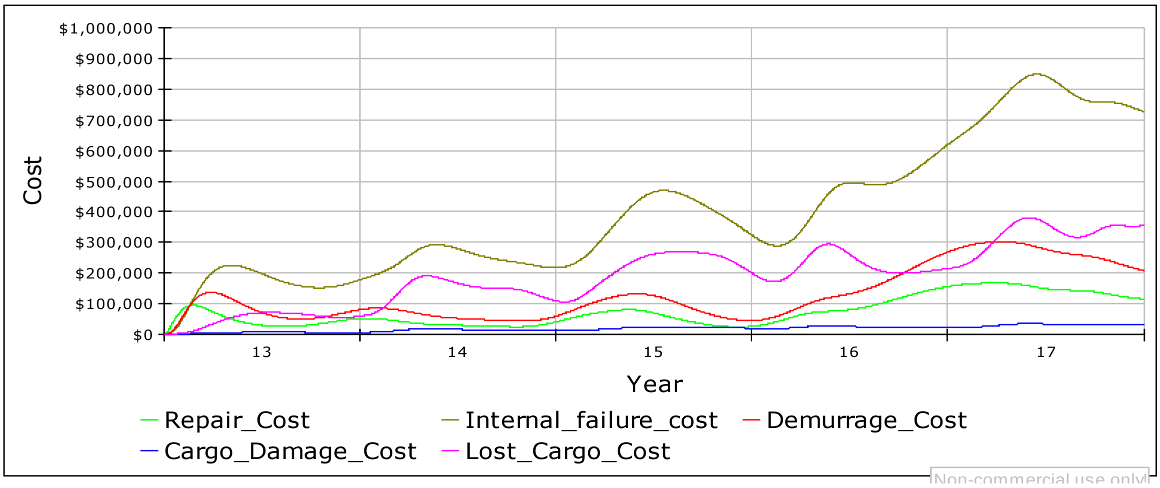
Table 37. Simulation results of the operation variables and cargo throughput

No	Operation variables	Maximum value
1	Number of unloaded vessels	31.0 Vessels/berths
2	Number of trucks	41.6 Trucks/berths
3	Number of tugboats	1 Boat/berths
4	Speed of conveyors	1.08 Meter/second
5	Cargo throughput in warehouse	133,604,177.67 Tons (cumulative)
6	Cargo throughput in stockpile yard	35,836,098.85 Tons (cumulative)

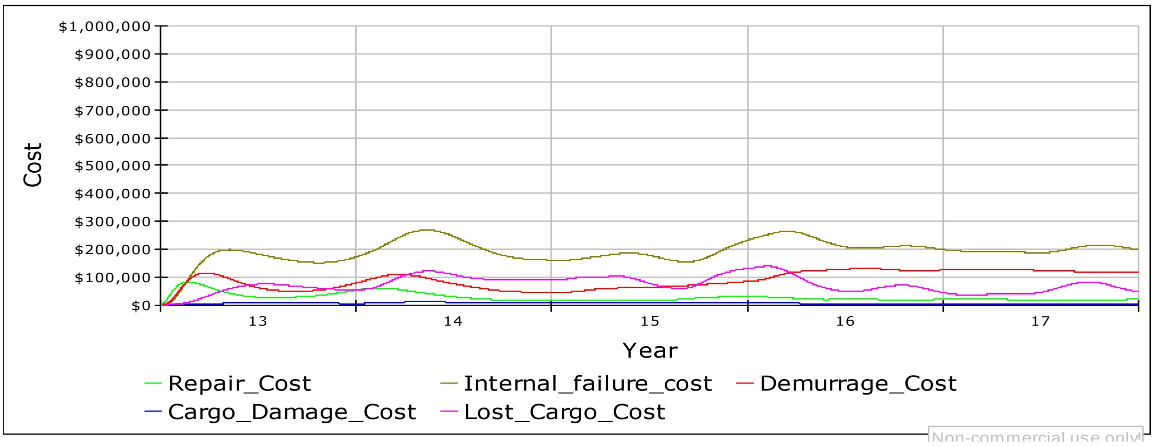
From Table 37 above, there are no changes before and after improvement scenarios. It means the increasing of the crane operation cycle and the crane lifting capacity do not have the effect of the operation variables and cargo throughput.

2. The port quality level

These improvement scenarios focus on decreasing the internal failure cost, which influences the cost of poor quality. Figure 81 below shows the behavior of the components of the internal failure cost as a non-conformance cost before and after improvements by simulation.



a) Before



b) After

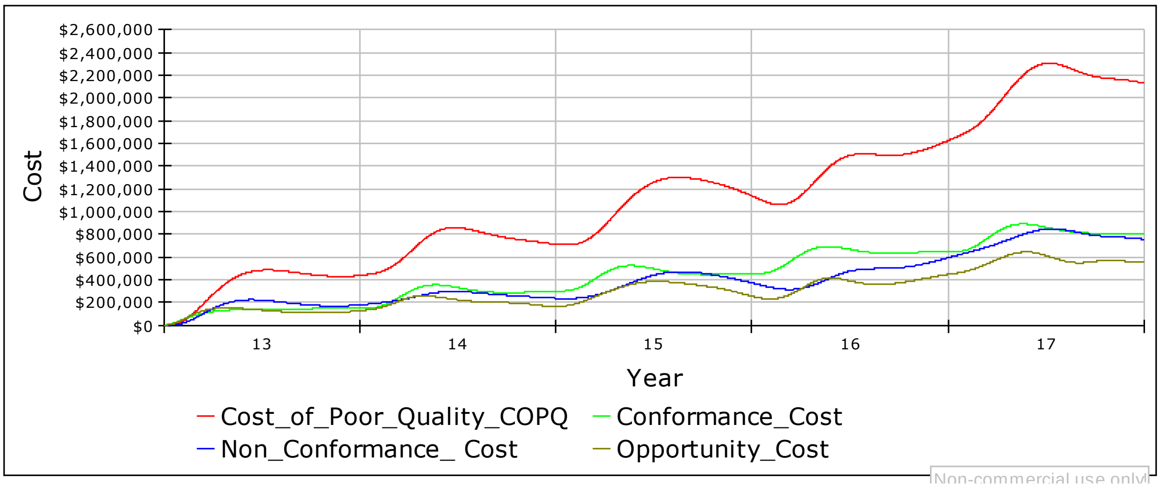
Figure 81. Trend of the internal failure cost before and after improvement by simulation: a) before improvement; b) after improvement

The simulation results for the average value before and after improvement are compared as depicted in Table 38 below:

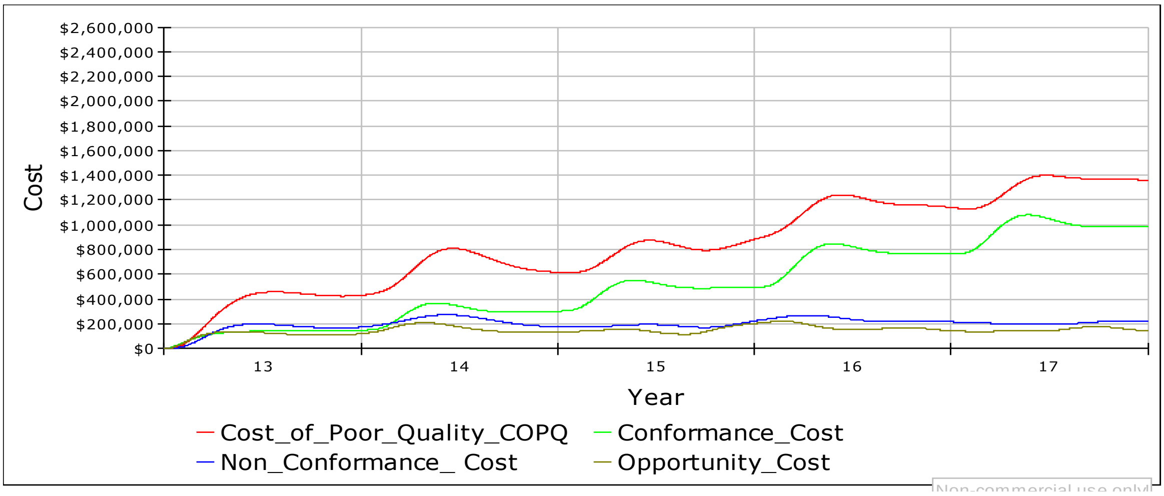
Table 38. Simulation results of the internal failure cost before and after improvement policies

No	Key performances indicators	Before ($)	After ($)	Decreasing (%)
1	Demurrage cost	150,101	90,143	40.0
2	Repair cost	87,304	27,489	68.5
3	Lost cargo cost	189,256	73,248	61.3
4	Internal failure cost	433,406	192,781	55.5
5	Opportunity cost	324,401	148,952	54.1
6	Cost of poor quality	1,184,944	854,249	27.9

From Table 38 above, the demurrage cost, repair cost, and lost cargo cost can be decreased by 39.95%, 68.51%, and 61.30% respectively. The total reduction of the internal failure cost is 55.52%. Related to this, the cost of poor quality can be reduced by 27.91%. Figure 82 below shows the trend of the COPQ components before and after improvement by simulation.



a) Before



a) After

Figure 82. Trend of the COPQ before and after improvement by simulation

The appraisal cost, as one of the conformance costs, will increase as a result of compensation for the decreasing non-conformance cost. From Table 36 below, the appraisal cost will increase by 15.16% as a compensation to reduce the internal failure cost as a non-conformance cost, especially the lost cargo cost. The 52.51% decrease in the non-conformance cost is 14.30% higher than the increase in the conformance cost. The comparison between conformance and non-conformance costs is presented in Table 39 below:

Table 39. Comparison between conformance and non-conformance cost

No	Cost components	Before	After	Change
		($)	($)	(%)
1	Prevention cost	12,960	12,154	-6.2
2	Appraisal cost	460,616	530,433	-15.2
3	Conformance cost	460,494	526,363	14.3
4	Non-conformance cost	424,131	201,439	-52.5

The trend of the comparison between the conformance and non-conformance costs can be seen in Figure 83 below:

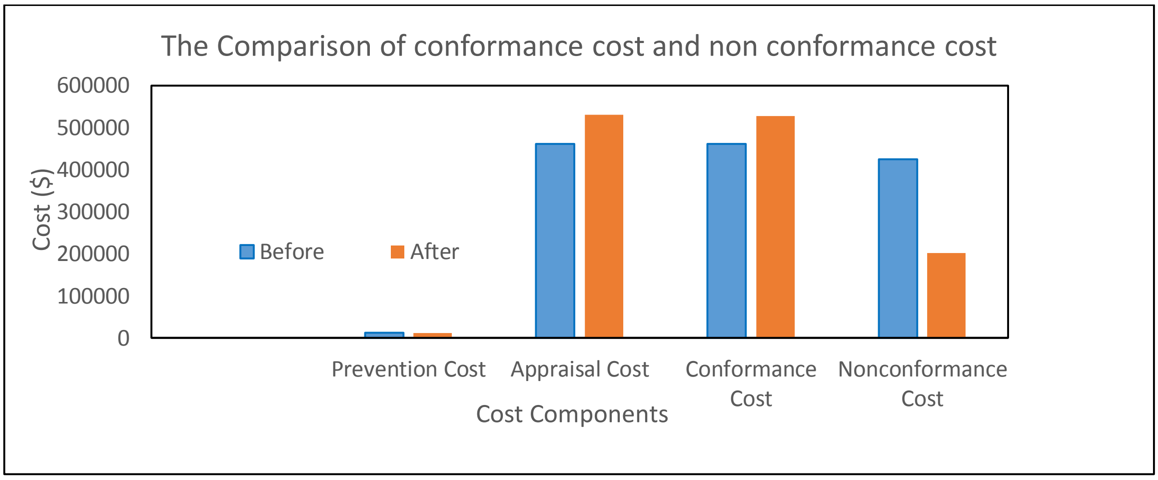
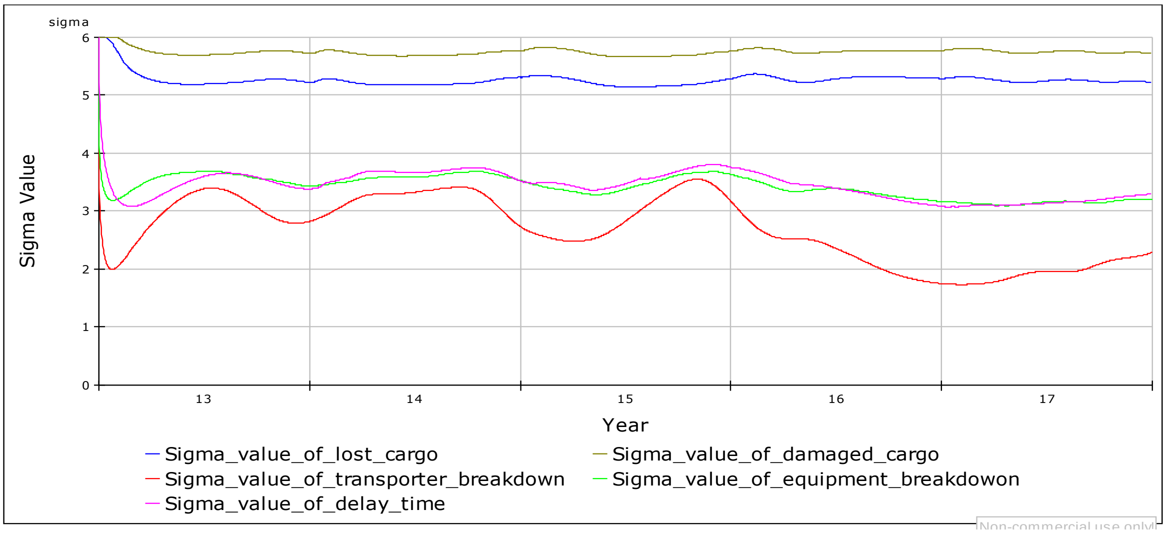


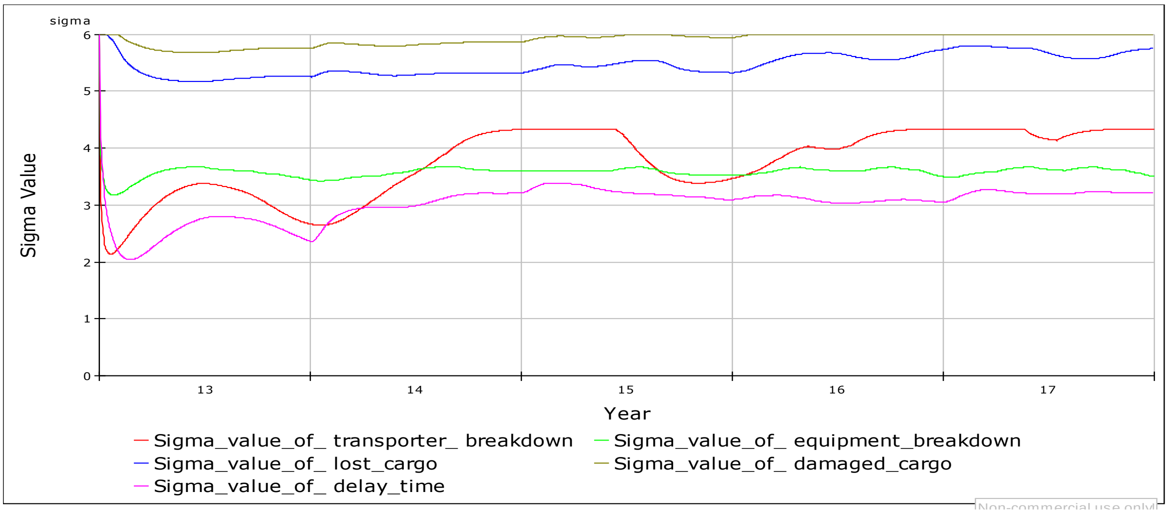
Figure 83. Comparison of the conformance cost and non-conformance cost

3. The port performance metrics

The behavior of the sigma value before and after improvement can be seen in detail in Figure 84 below.



a) Before



b) After

Figure 84. Comparison of the sigma values for all areas of port performance

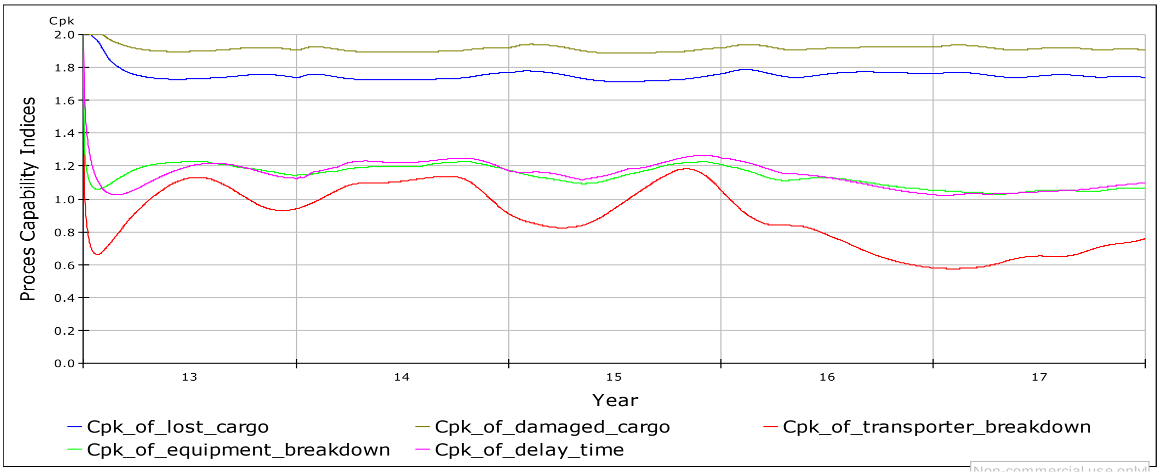
From Figure 84, all the sigma values have been increased after the improvement except the delay time, which is because increasing the number of transport maintenance items has the effect of increasing the delay time due to maintenance. The six sigma of the transporter breakdown has increased sharply by 39.71% as a result of increasing the number of transport maintenance items. The sigma value of the lost and damaged cargo was the highest sigma, both before and after the scenario of improvements. Meanwhile, the sigma values of equipment and transporter breakdown and delay time were the lowest sigma before and after the scenario of improvements. The high and low sigma indicate the quality of the waste. The higher the sigma value, the less waste in the port. Nevertheless, all types of waste must be improved to achieve a lean supply chain in the port. From the simulation results, the average value before and after the improvement scenarios as the degree of quality improvement in the port performance, can be seen in Table 40 below:

Table 40. Sigma value of the port performance before and after improvement by simulation

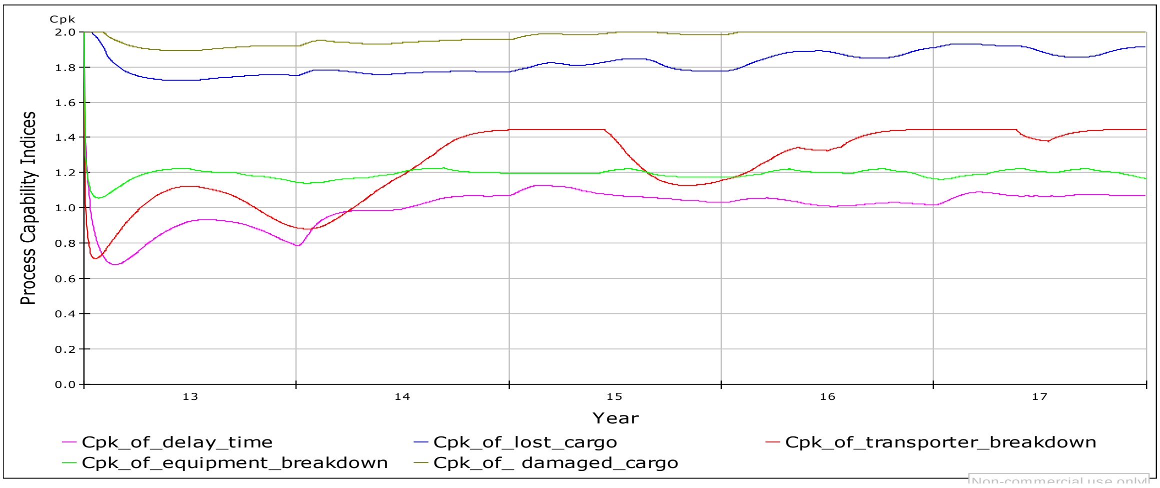
No	Sigma value of the waste in port	Before ($)	After ($)	Change (%)
1	Sigma value of lost cargo	5.26	5.47	4.0
2	Sigma value of damaged cargo	5.74	5.91	3.0
3	Sigma value of transporter breakdown	2.72	3.80	39.7
4	Sigma value of equipment breakdown	3.46	3.62	4.6
5	Sigma value of delay time	3.47	3.06	-11.8

The trend of the sigma value can be seen in detail in Figure 84 below.

The behavior of the process capability indices before and after improvement can be seen in detail in Figure 85 below.



a) Before



b) After

Figure 85. Comparison of the Cpk for all areas of port performance

From Figure 85 above, all the Cpk have been increased after the improvements except the delay time, because increasing the number of transport maintenance items has the effect of increasing the delay time due to maintenance. The Cpk of transporter breakdown increased significantly by 39.56% as a result of increasing the number of transport maintenance items. Similarly to the sigma value, the highest Cpk was for lost and damaged cargo, both before and after the scenario of improvements. Meanwhile, the Cpk values of equipment and transporter breakdown and delay time have the minimum value both before and after the scenario of improvements. The high and low Cpk values denote the process capability of the port to eliminate waste. The higher the Cpk, the greater the capability to eliminate waste in the port. This simulation can help to monitor Cpk values over time and to take actions to reduce or eliminate waste so that the lean supply chain is achieved.

From the simulation results, the process capability indices (Cpk) in the average value before and after the improvement scenarios as the degree of quality improvement in the port's performance, can be seen in Table 41 below:

Table 41. Process capability indices of port performance before and after improvement by simulation

No	Cost Components	Before	After	Change
		($)	($)	(%)
1	Cpk of lost cargo	1.75	1.82	4.0
2	Cpk of damaged cargo	1.91	1.97	3.1
3	Cpk of transporter breakdown	0.91	1.27	39.6
4	Cpk of equipment breakdown	1.15	1.21	5.2
5	Cpk of delay time	1.16	1.02	-12.1

The behavior reflected in the measurement of the sigma value and Cpk in Figures 84 and 85 above follows the structure of the goal seeking after the improvements. This is because the trend of the sigma value will try to reach the goal of the six sigma value and the trend of Cpk will try to seek the target value in Cpk 2.0. The goal-seeking behavior arises due to the negative feedback loop structure. There are discrepancies between the actual and the desired sigma values and Cpk's. The improvement scenarios are addressed to obtain the behavior of the actual sigma value and Cpk, so as to achieve the desired value.

Chapter 8

Conclusions and Future Research

8.1 Conclusions

An integrated model of the port operation and the port quality level is built based on the causal relationship between several variables. The causal relationship and the behavior of complex variables in ports can be investigated dynamically. A system dynamics approach is a suitable tool that can be applied to investigate the behavior of the port system.

The port performance is measured with the performance metrics, namely the sigma value, the process capability indices, and the cost of poor quality. These metrics are utilized to eliminate waste in order to improve the lean supply chain in the port. This waste consists of lost and damaged cargo, equipment and transporter breakdown, and equipment and transporter delay time.

The behavior of the port operation model oscillates because the state of the system is seeking to reach an equilibrium condition. Growth with overshoot will happen in the behavior of the port system as the system tries to achieve the target due to delay factors in the system. Meanwhile, the behavior of the port quality level model shows growth with overshoot. Sometimes, there will be an overshoot and collapse in the behavior of the port quality level. Finally, the behavior of the port performance metrics follows the goal-seeking structure to reach the desired value.

Regarding the base case simulation results, the berth occupancy ratio (BOR) reaches a maximum value of 89.29%, which affects the vessel waiting time of 3.00 day/vessel. The demurrage cost contributes more to the non-conformance cost than the other costs in the internal failure cost, followed by the repair cost and lost cargo cost. These values become the main issue for the improvement scenarios.

The vessel waiting time and the internal failure cost as waste in ports are decreased by the improvement scenarios through system dynamics simulation. For the case study, due to the scenario in which the customer order rate of dry bulk cargo increases by 5.4% per year, the BOR will reach an average value of 89.33%, with a vessel waiting time of 7.71 day/vessel. Also, the internal failure cost is increased, and especially the demurrage cost, lost cargo cost, and repair cost. After the improvements, the BOR will reach an average value of 38% and the vessel waiting time will be 0.01 day/vessel about 15 minutes/vessel. The vessel waiting time is decreased by 99.87%. All internal failure costs as non-conformance cost components have been decreased after the improvements. The demurrage cost and repair cost are decreased by 40% and 69% respectively. Also, the lost cargo cost is decreased by 61%. On the contrary, the appraisal cost as conformance cost will increase by 15% as compensation to reduce the internal failure cost.

According to the results of the improvement scenarios, it can be concluded that increasing the crane operation cycle and lifting capacity can reduce the vessel waiting time as a key performance indicator in the port. Also, the increase in the number of transporter maintenance items, the inspector numbers, and the safety and security cost can reduce the demurrage, repair, and lost cargo costs.

The cost of poor quality decreases and it will improve the lean supply chain at ports by the improving of the sigma value and the process capability indices (Cpk) of waste in ports as performance metrics. For the case study, the cost of poor quality is decreased by 28% so that it will improve the lean supply chain in the port. After the improvements, sigma value and process capability indices (Cpk) of the transporter breakdown can be improved sharply by 39.7% and 39.6%. The sigma value of the lost cargo; damaged cargo; and equipment breakdown can be improved by 4.0%; 3.0%, and 4.6%. Meanwhile, Cpk of the lost cargo; damaged cargo; and equipment breakdown can be improved by 4.0%; 3.1%, and 5.2%. With this model, changes in the sigma value and Cpk of the waste can be identified and the results analyzed so as to take action. All areas of waste must be reduced or eliminated to achieve a lean supply chain in the port.

8.2 The Future Research

The model of the port operation has been developed gradually without considering the equipment and transporter maintenance activity directly in the material flow. However, there are still exogenous variables related to this maintenance activity. In the real case, the operation cycle of the crane and the number of truck operation cycles are influenced by the availability of equipment and transporters. This availability will be influenced by both preventive and corrective maintenance activity. All operations in ports that relate to the capacity and utilization must be explained in more detail, including the berth occupancy ratio (BOR) and the vessel waiting time. By considering these variables, new feedback loops are expected in future research.

The model of the port operation has also been designed without considering the cost of investments. This means that there are no limits on the cost of investments. Hence, variables that reflect the investment cost should be constructed to make the model more realistic. By developing new variables, new feedback loops are expected to emerge in the new model, making it more accurate under the dynamic conditions. Decision makers will have a role in developing the feedback loop.

The policy of improvement scenarios has been constructed by trials of the interventions of exogenous variables to identify the best solution. In future, the use of factorial experiments method is proposed to formulate the best improvement scenarios. This method can determine all factors that influence the respond variables. The changing of input parameters as the independent variables must be controlled to achieve the optimal solution. Also, the interval limit of the input parameters must be added or increased to know their effect.

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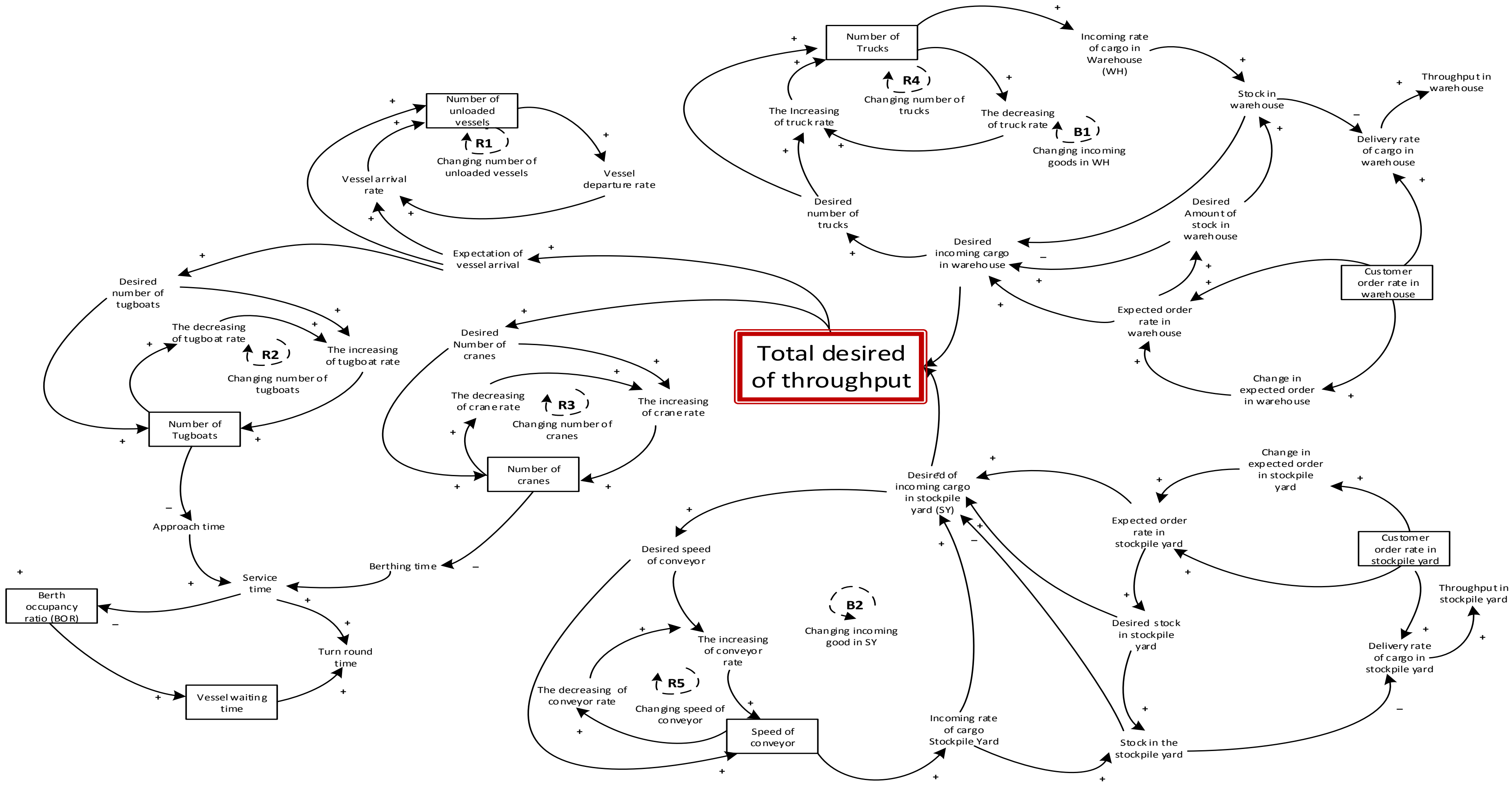
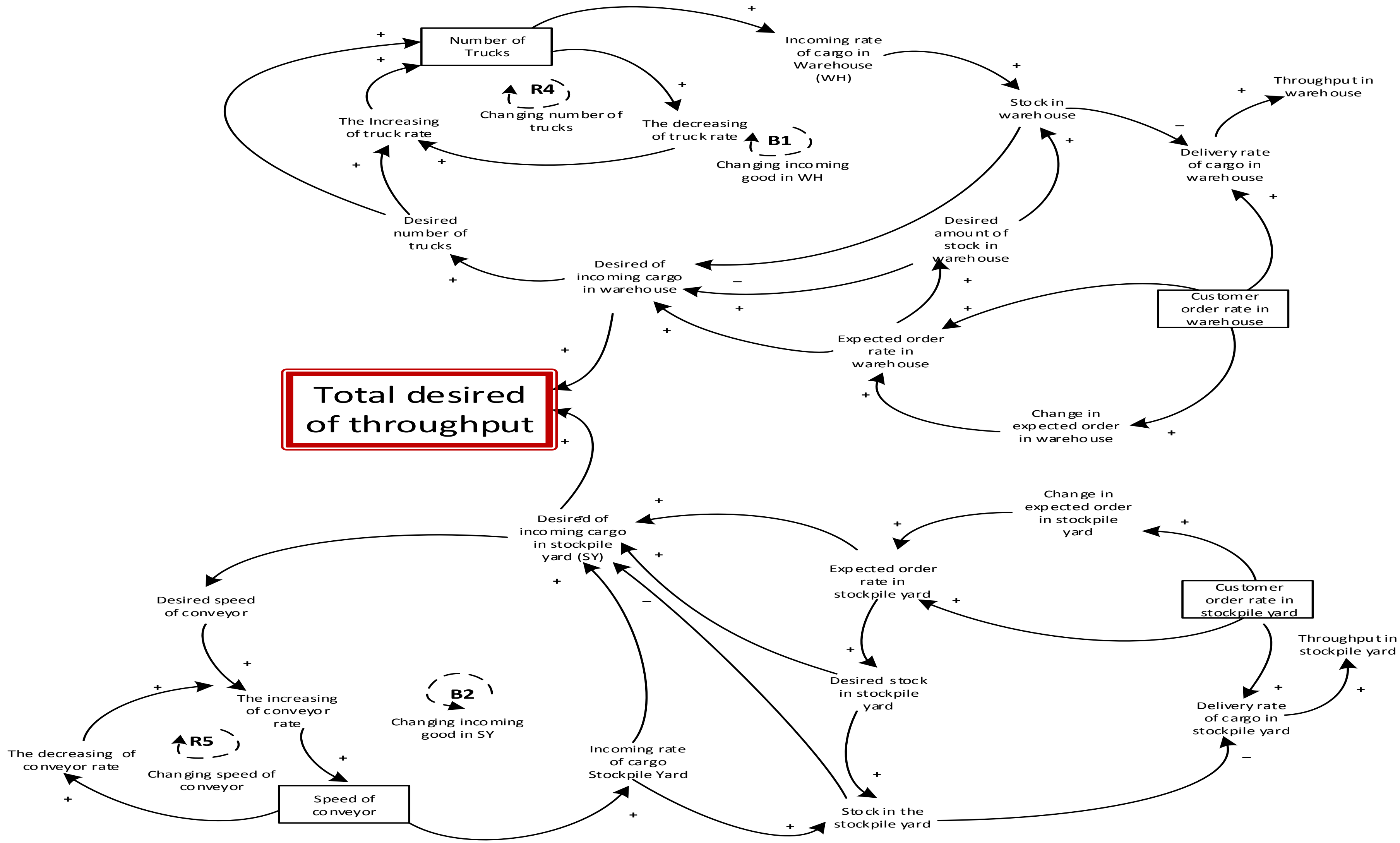
Appendix A: Causal Loop Diagram (CLD)

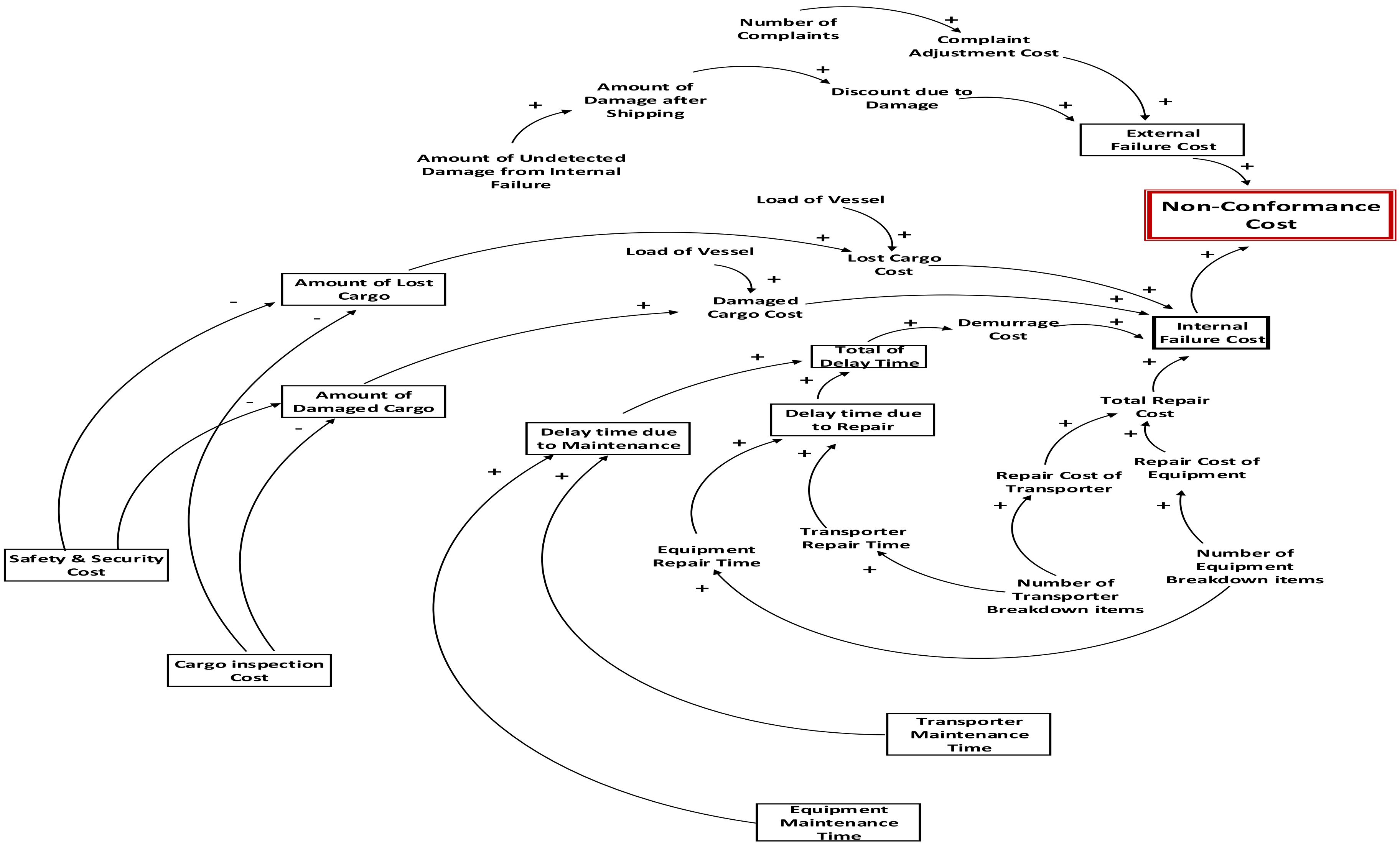
A.1: The CLD of the port operation



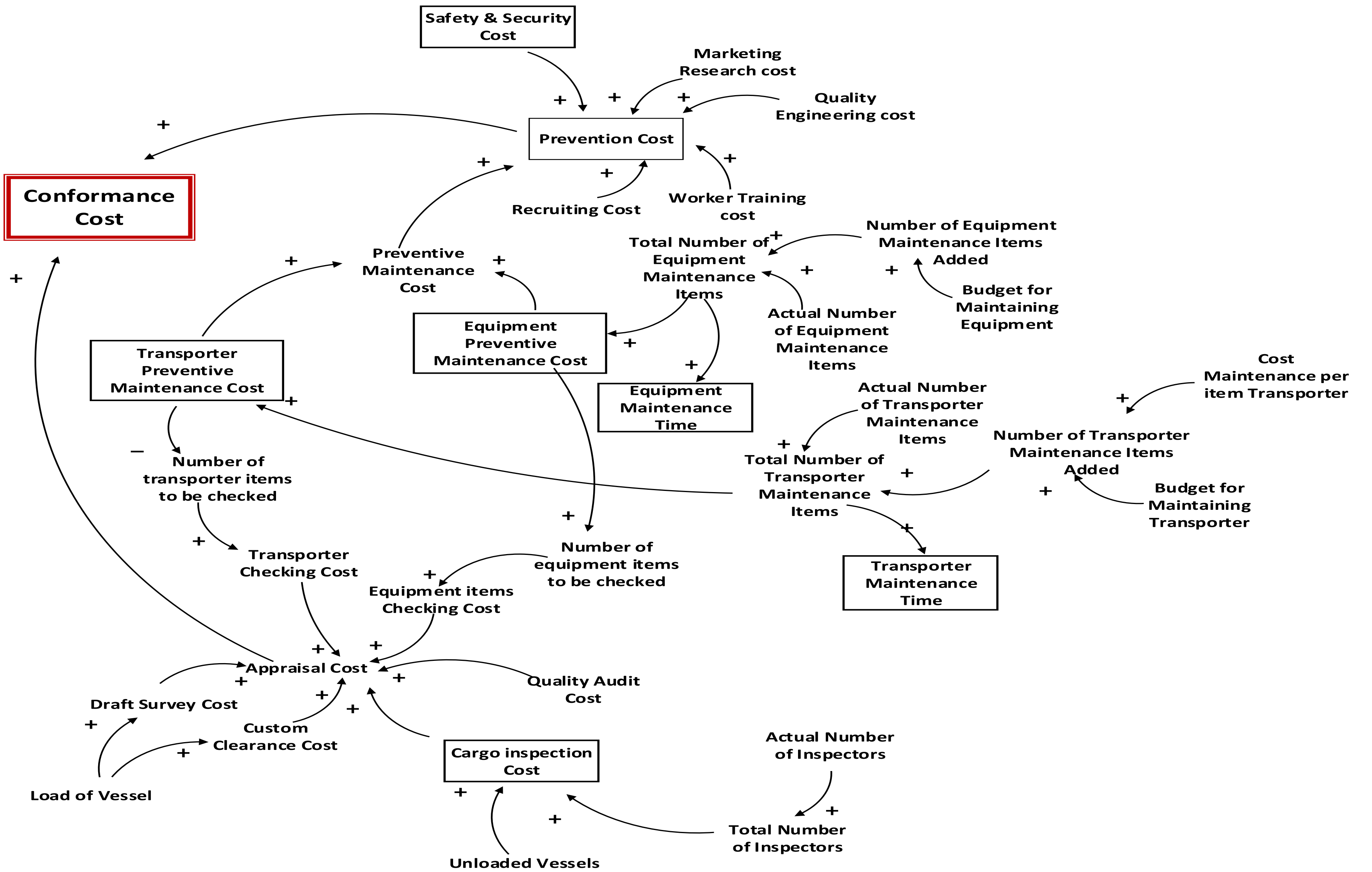
A.2: The CLD of the land side in the port operation



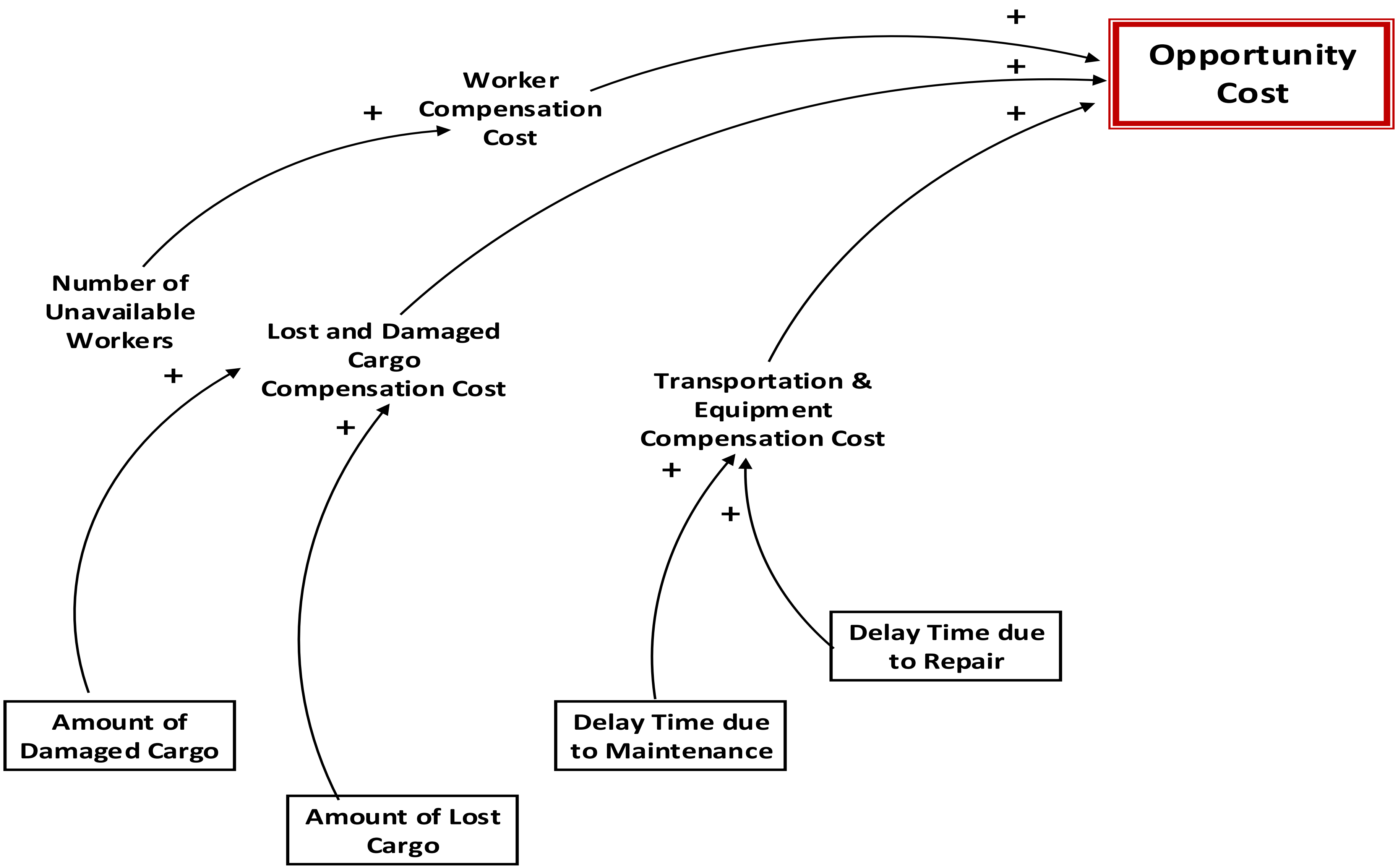
A.3: The CLD of the non-conformance cost



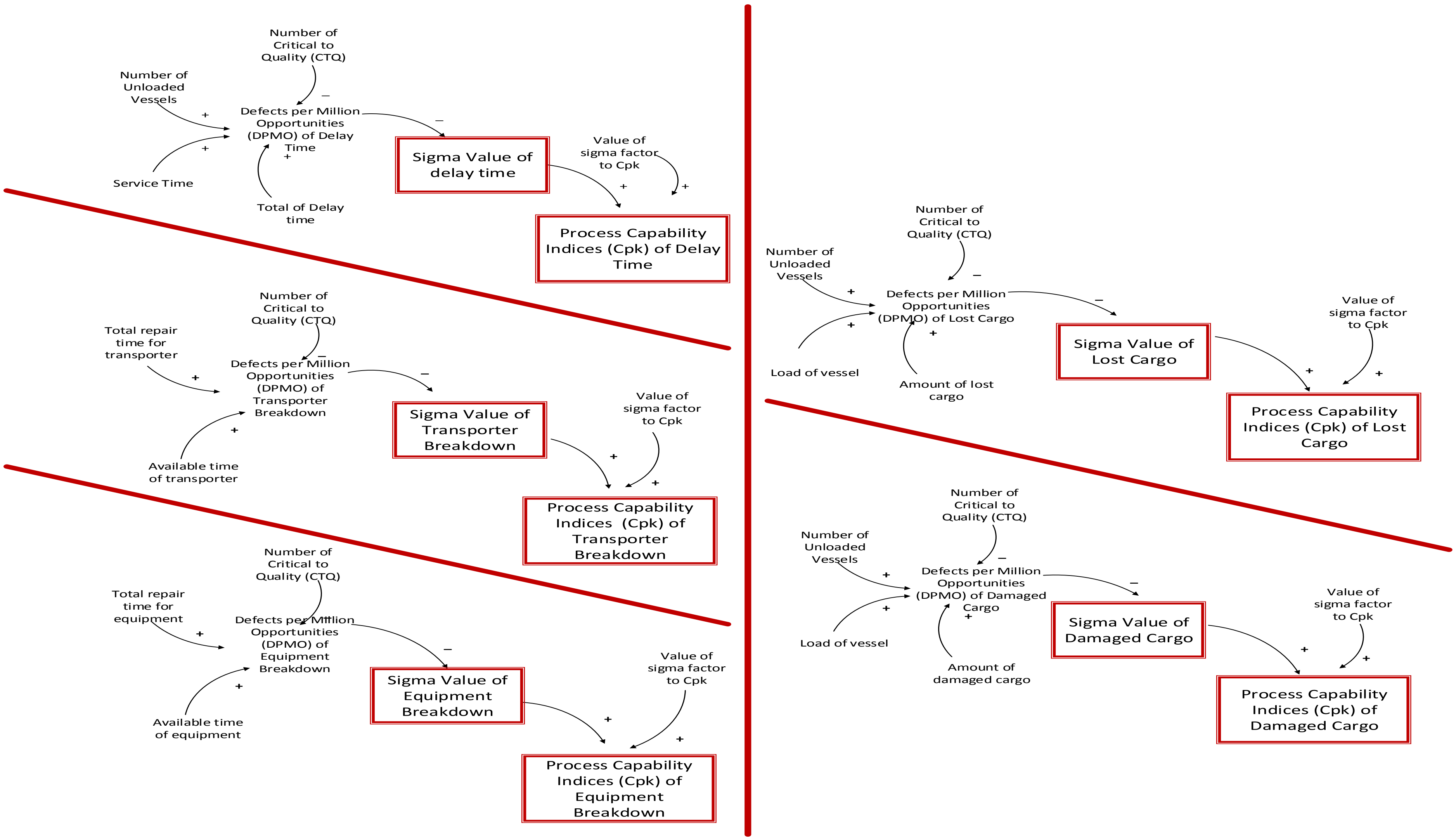
A.4: The CLD of the conformance cost



A.5: The CLD of the opportunity cost

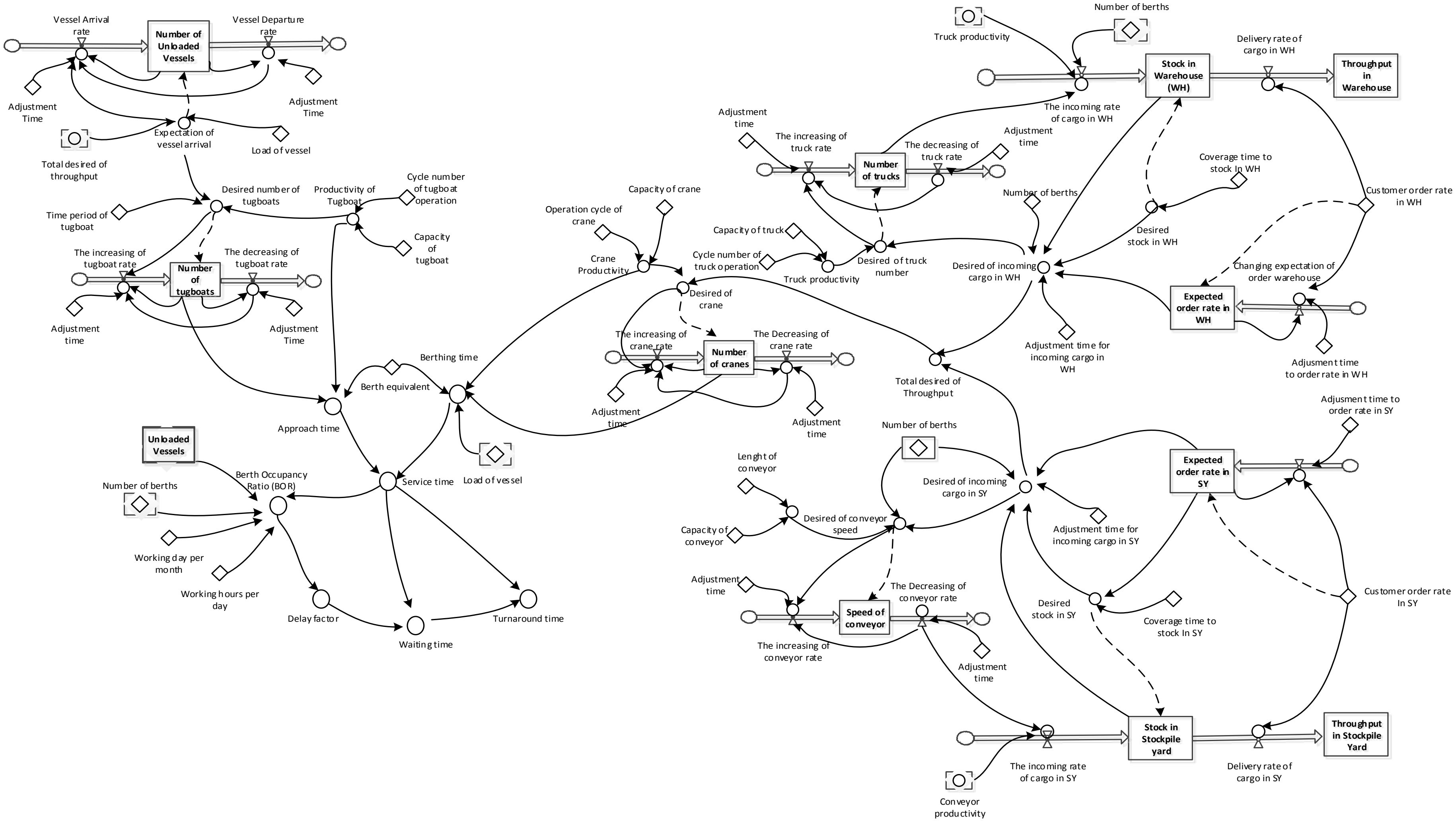


A.6: The CLD of the port performance metrics

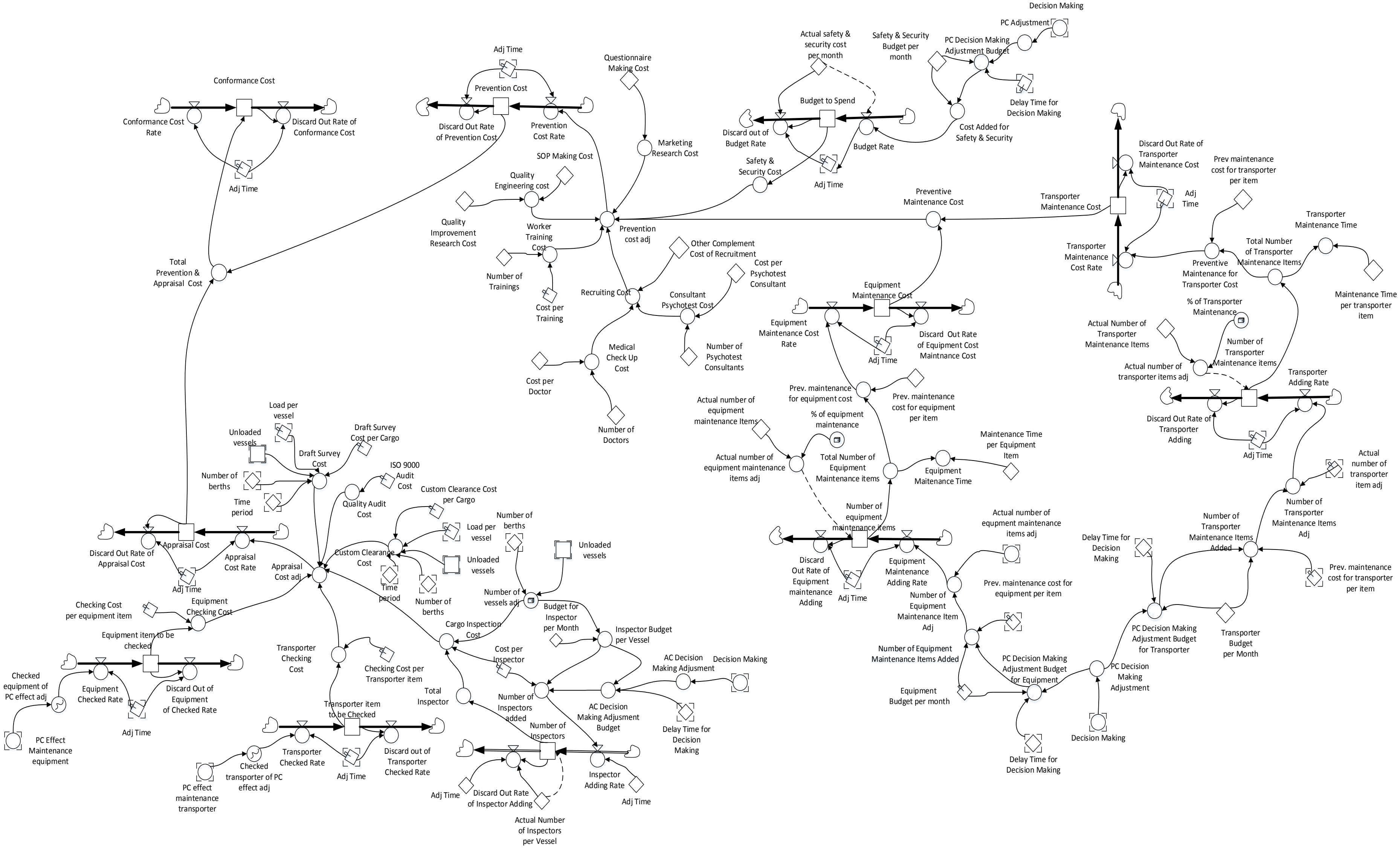


Appendix B: Stock Flow Diagram (SFD)

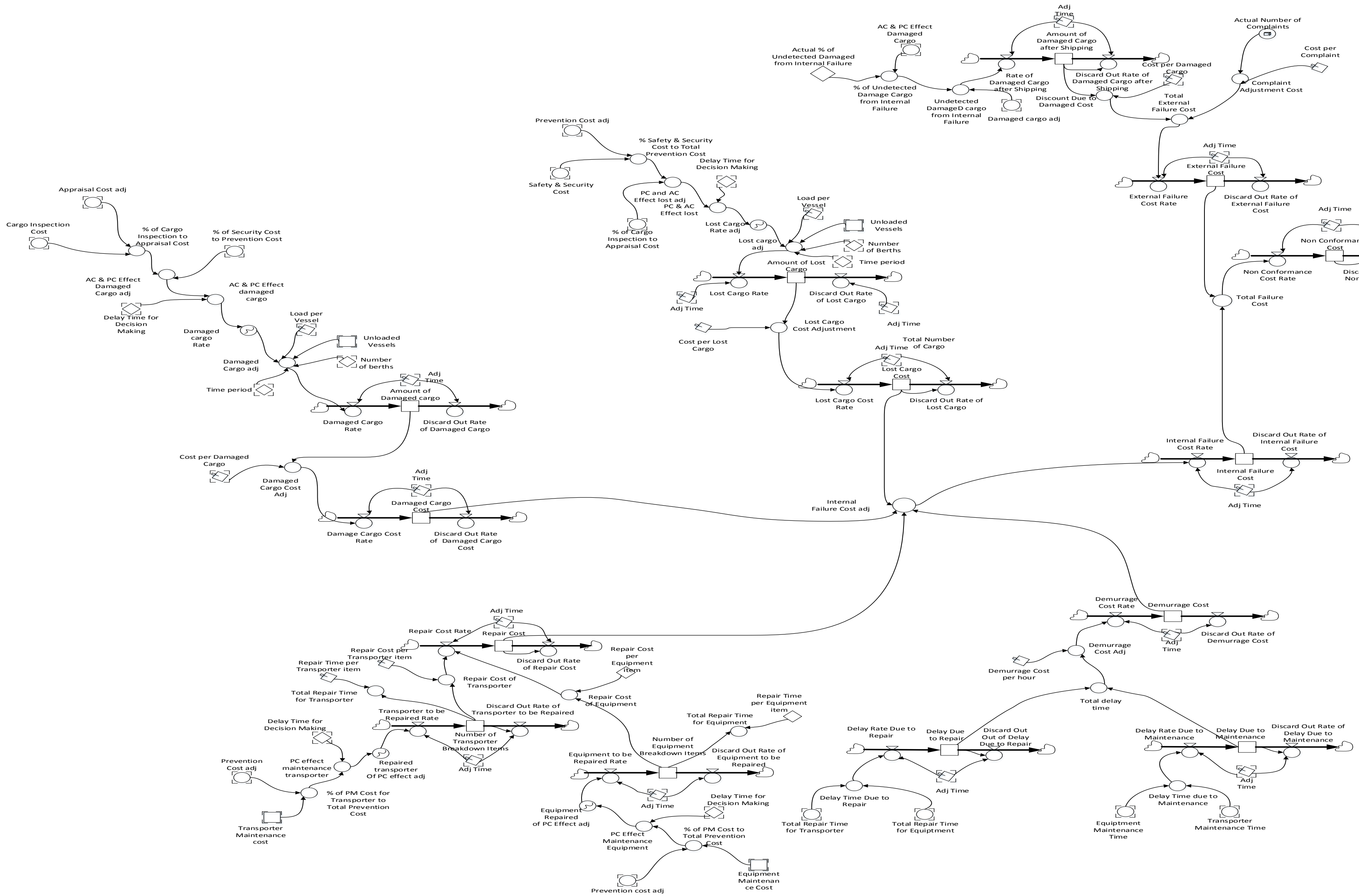
B.1: The SFD of the port operation



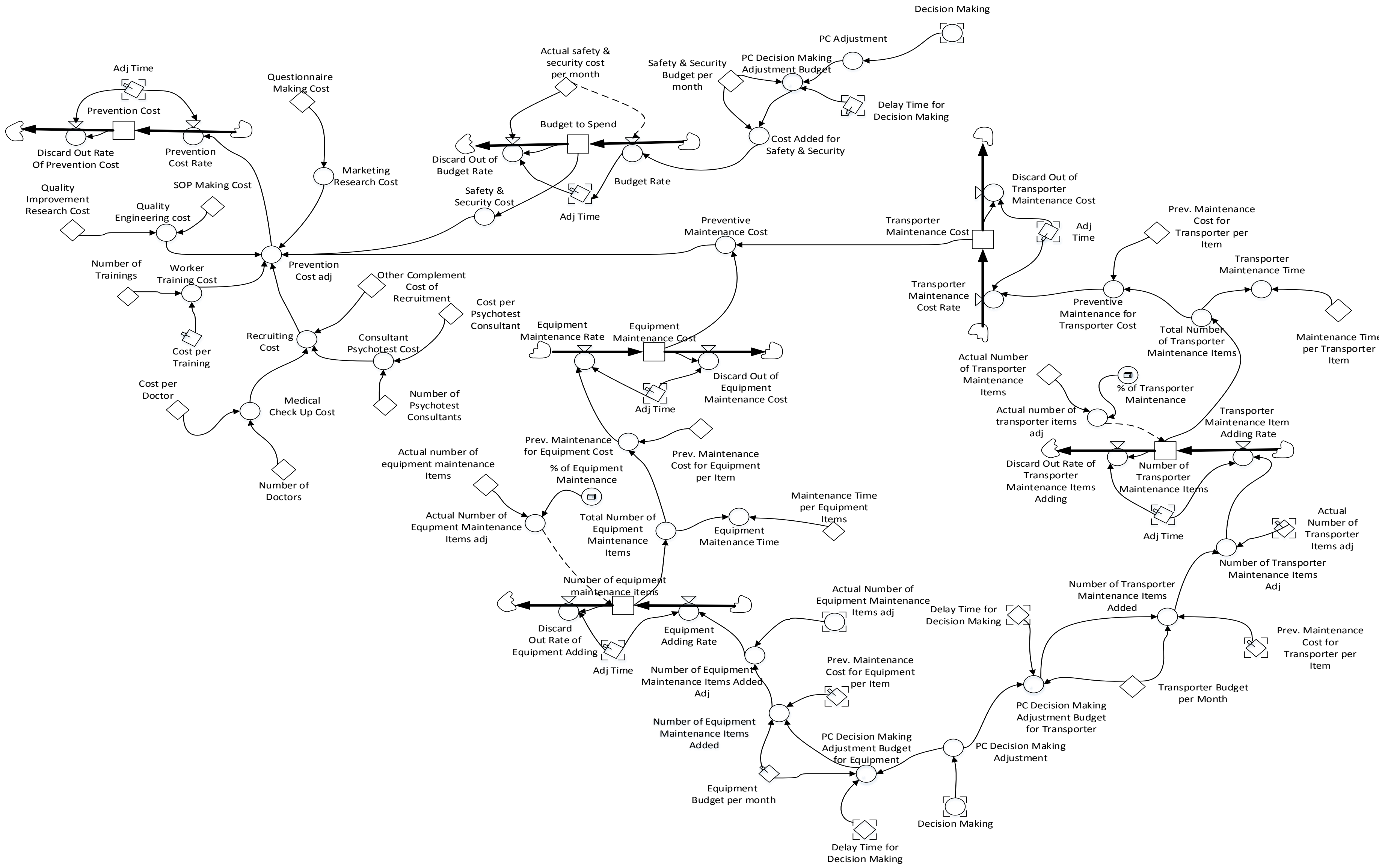
B.2: The SFD of the conformance cost



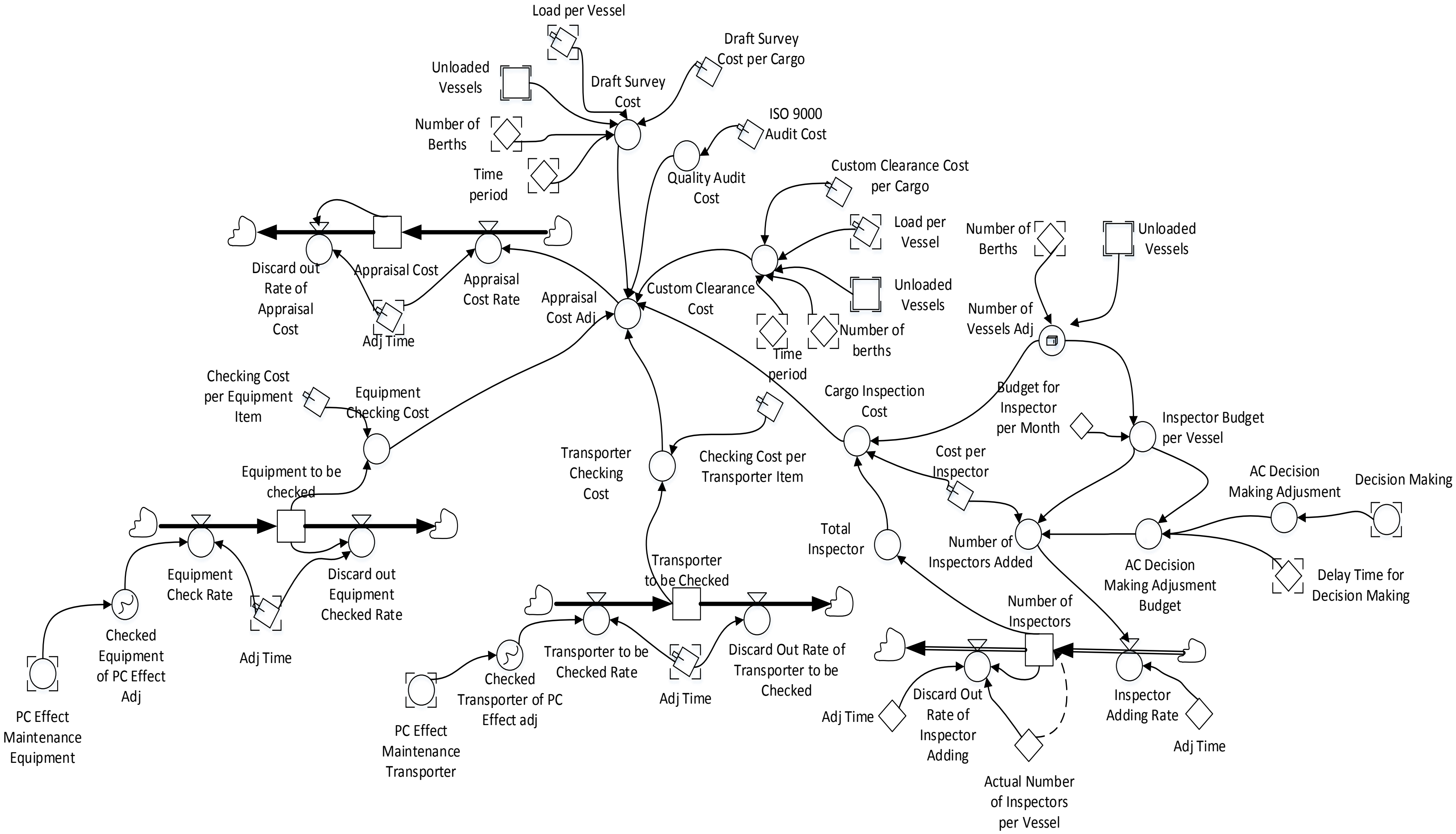
B.3: The SFD of the non-conformance cost



B.4: The SFD of the prevention cost



B.5: The SFD of the appraisal cost



Appendix C: Data of Vessel Report and Actual Cost of Poor Quality in 2013

C.1: Data of vessel report in 2013

Month	Unloaded of Vessels	Cargo Throughput by Truck (Tons)	Cumulative of cargo throughput by truck (Tons)	Cargo Throughput by conveyor (Tons)	Cumulative of cargo throughput by conveyor (Tons)	Average of the load of vessel (Tons)	Service Time (day/ vessel)	Vessel waiting Time (hour/ vessel)	Berth Occupancy Ratio (BOR) %
January	46	643393	643393	145952	145952	17160	4.93	4.84	72.71%
February	44	697657	1341050	160097	306049	19494	4.45	5.53	70.50%
March	49	627443	1968493	0	306049	12805	3.51	4.71	54.01%
April	46	749638	2718131	158270	464319	19737	5.04	4.58	73.05%
May	43	710307	3428438	149690	614009	20000	3.56	3.31	57.72%
June	53	803358	4231796	0	614009	15158	5.54	5.87	83.01%
July	46	822368	5054165	156947	770956	21289	4.28	7.28	80.23%
August	44	800920	5855084	161308	932264	21869	5.24	4.6	65.49%
September	31	381197	6236281	0	932264	12297	4.84	3.79	39.84%
October	48	534782	6771063	55078	987342	12289	3.55	4.95	60.33%
November	45	726821	7497883	402815	1390158	25103	4.3	3.73	81.50%
December	50	787802	8285685	17937	1408095	16115	4.65	4.47	74.74%

C.2: Actual data of cost of poor quality in 2013

Month	Internal Failure Cost	External Failure Cost	Non-Conformance Cost	Appraisal Cost	Prevention Cost	Conformance Cost	Opportunity Cost	Cost of Poor Quality
January	$146,087.37	$15,385.00	$161,472.37	$135,355.17	$2,608.92	$137,964.09	$86,724.84	$386,161.30
February	$114,383.46	$12,308.00	$126,691.46	$80,249.38	$3,191.66	$83,441.04	$94,209.02	$304,341.52
March	$154,807.99	$12,308.00	$167,115.99	$89,690.04	$4,428.38	$94,118.42	$75,560.30	$336,794.71
April	$129,656.25	$12,308.00	$141,964.25	$144,610.17	$3,206.71	$147,816.88	$82,389.65	$372,170.78
May	$241,165.23	$12,308.00	$253,473.23	$95,150.73	$2,544.95	$97,695.68	$56,935.58	$408,104.49
June	$117,256.24	$12,308.00	$129,564.24	$175,288.90	$5,006.00	$180,294.90	$43,914.39	$353,773.53
July	$149,884.49	$12,308.00	$162,192.49	$156,096.09	$6,427.84	$162,523.93	$96,241.84	$420,958.26
August	$143,741.81	$15,385.00	$159,126.81	$140,609.52	$4,081.31	$144,690.83	$48,760.85	$352,578.49
September	$115,191.06	$12,308.00	$127,499.06	$144,300.08	$2,098.35	$146,398.43	$89,763.77	$363,661.26
October	$117,735.57	$12,308.00	$130,043.57	$92,199.36	$2,167.05	$94,366.41	$82,322.63	$306,732.61
November	$152,470.55	$15,385.00	$167,855.55	$177,316.29	$3,230.44	$180,546.73	$102,518.85	$450,921.13
December	$104,782.45	$9,231.00	$114,013.45	$194,642.82	$3,849.21	$198,492.03	$60,782.55	$373,288.03

Appendix D: Constants, Functions, and Equations in Model Simulations

D.1: Constants, functions, and equations in the port operation

D.1.1: Constants in the port operation

No	Contants	Unit	Value
1	Capacity_of truck	ton/(truck*cycle)	30<<ton/cycle/truck>>
2	Cycle_number_of_ truck_operation	cycle/da	12<<cycle/da>>
3	Cycle_number_of_ tugboat_operation	cycle/da	5<cycle/da>>
4	Capacity_of_ tugboat	vessel/(boat*cycle)	0.5<<vessel/boat/cycle>>
5	Length_of_conveyor	km	7<<km>>
6	Capacity_of_ conveyor	ton/hour	3000<<ton/hour>>
7	Operation_cycle_of_crane	cycle/da	315<<cycle/da>>
8	Lifting_capacity_of_crane	ton/(crane*cycle)	14<<ton/crane/cycle>>
9	Adjusment_time_for_decreasing_and increasing of crane, truck, conveyor, tugboat,	mo	1<<mo>>
10	Customer order rate in SY	ton/mo	185203<<tons/mo>>
11	Working_day _per _month	da	30<<da>>
12	Working_hours _per_day	hr	24<<hr/da/berths>>
13	Number_of_berths	berths	10<<berths>>
14	Load_of_vessel	ton/(mo*vessel)	18225<<tons/mo/vessel>>
15	Coverage_time to stock in warehouse and stockpile yard	mo	1<<mo>>
16	Adjustment_time for incoming cargo in warehouse and stockpile yard	mo	1<<mo>>
17	Customer Order Rate in WH	ton/mo	690474<<tons/mo>>
18	Adjustment_time to order rate in warehouse and stockpile yard	mo	1<<mo>>

D.1.2: Functions and equations in the port operation

No	Variables	Type	Unit	Equations
1	Number of cranes	Stock	crane/ berths	Number_of_cranes = **INTEGRAL** (Adding_rate_of_crane – Decreasing_rate_of_ crane) + Desired_number_of crane
2	Number of unloaded vessels	Stock	vessel/ berths	Number_of_unloaded_vessels = **INTEGRAL** (Vessel_arrival_rate – Vessel_departure_rate) + Desired_number_of _unloaded_vessels
3	Throughput in stockpile yard (SY)	Stock	tons	Throughput_in_SY = **INTEGRAL** (Delivery_rate_of _cargo_in_SY) + 0<<ton>>
4	Throughput in warehouse (WH)	Stock	tons	Throughput_in_WH = **INTEGRAL** (Delivery rate of cargo in WH+ 0<<ton>>
5	Speed of conveyor	Stock	m/s	Speed_of_conveyor = **INTEGRAL** (The_decreasing_of_convey_rate - The_increasing_of _conveyor_rate)+Desired_speed_of_ conveyor
6	Expectation of order (SY)	Stock	tons/mo	Expectation_of_ order_SY = **INTEGRAL** (Change_in_order _expectation_SY) + Order Rate_SY
7	Stock in the stockpile yard (SY)	Stock	tons	Safety_stock_in_the _stockpile_ yard_SY= **INTEGRAL** (Incoming_rate_of cargo in SY - Delivery_rate_of_ cargo_in_SY +Expectation_of desired_ throughput_in_SY
8	Number of tugboats	Stock	boat/berths	Number of tugboats= **INTEGRAL** (The_increasing_of _tugboat_rate - The_decreasing_of_tugboat_rate) +Desired_number_of_tugboats
9	Number of trucks	Stock	truck/berths	Number_of_trucks= **INTEGRAL** (The_increasing_of _truck_rate - The_decreasing_of_ truck_ rate) +Desired_number_of_trucks
10	Expectation of order (WH)	Stock	tons/mo	Expectation_of_ order_WH = **INTEGRAL** (Change_in_order _expectation_WH) +Order_rate_in_ WH
11	Stock in warehouse (WH)	Stock	tons	Safety_stock_in warehouse_WH= **INTEGRAL** (Incoming_rate_of cargo in WH - Delivery_rate_of_ cargo_in_WH+Expectation_of_ desired_throughput_in_WH
12	Productivity of truck	Auxiliary	tons/ (da*truck)	Capacity_of truck*cycle_number_of_ truck_operation
13	Productivity of tugboat	Auxiliary	vessel/ (da*boat)	Capacity_of_ tugboat*cycle_number_of_ tugboat_operation
14	Productivity of conveyor	Auxiliary	tons/ (da*km)	Capacity_of_ conveyor/length_of_conveyor
15	Decreasing rate of crane	Flow	crane/ (mo*berths)	Number_of_cranes/adjusment_time_for_decreasing_crane
16	Adding rate of crane	Flow	crane/ (mo*berths)	(Desired_number_of_cranes-Number_of_cranes)/ adjusment_time_for_adding_crane+Decreasing_rate_of_crane
17	Total desired of throughput	Auxiliary	tons/ (mo*berths)	Desired_throughput_in_SY+Desired_throughput_in_WH
18	The decreasing of conveyor rate	Auxiliary	m/s^2	Speed_of_conveyor/Adjustment_time _for_decreasing _conveyor

19	The increasing of conveyor rate	Auxiliary	m/s^2	(Desired_speed_of_conveyor-Speed_of_conveyor)/ Adjusment_time_for_increasing_of_ conveyor'+The_decreasing_of_conveyor_rate
20	Desired speed of conveyor	Auxiliary	m/s	MAX(0<<m/s>>,(Number_of_berths*Desired_throughput_in_SY)/'Productivity_of_ conveyor')
21	Desired throughput in SY	Auxiliary	tons/(mo* berths)	(Expectation_of_ order_SY'+('Expectation_of desired_ throughput_in_SFY-Safety_stock_in_the_stockpile_yard_SY)/Adjustmenttime_for_changing_throughput _ in_SY')/Number_of_berths
22	Expectation of desired throughput in SFY	Auxiliary	tons	Expectation_of_ order_SY'*'Coverage_time_ for_throughput_in _SFY
23	Change in order expectation (SY)	Flow	tons/mo^2	(Order Rate_SY-Expectation_of_ order_SY)/Adjustment_time_of_expectation_SY
24	Incoming rate of cargo in SY	Flow	tons/mo	Speed_of_conveyor*Productivity_of_ conveyor
25	Delivery rate of cargo in SY	Flow	tons/mo	Order Rate_SY
26	Turnaround time	Flow	da/vessel	Service_time+Waiting_time
27	Waiting time	Auxiliary	da/vessel	Delay_factor*Service_time
28	Delay factor	Auxiliary	%	((1.563e18)*EXP(43*('Berth_Occupancy_Ratio_BOR'/100<<%>>)))+(0.0001014*EXP(9.523*('Berth_ Occupancy_ Ratio_BOR'/100<<%>>)))
29	Desired of berth occupancy ratio (BOR)	Auxiliary	%	(Number_of_unloaded_vessels*Service_time)/(Number_of_berths*'Working_day _per _month'*'Working_hours _per_day')*Number_of_berths*100<<%>>
30	Service time	Auxiliary	da/vessel	Approach time+Berthing_time
31	Approach time	Auxiliary	da/vessel	(1/(productivity_of_ tug_boat*Number of tugboat))/Berth_equivalent
32	Desired number of tugboats	Auxiliary	boat/berths	MAX(0<<boat/berth>>CEIL(((Expectation_of _vessel_arrival/productivity_of_ tug_boat)/Time_period_of_ tugboat_operation),1<<boat/berth>>))
33	The decreasing of tugboat rate	Flow	boat/ (mo*berths)	Number of tugboats/Adjustment_time _for_decreasing _tugboat
34	The increasing of tugboat rate	Flow	boat/ (mo*berth)	(Desired_number_of_tugboats-Number of tugboats)/Adjusment_time_for_increasing_of_ tugboat+The_decreasing_of_tugboat_rate
35	Vessel departure rate	Flow	vessel/ (mo*berths)	Unloaded_vessels/Time_adjustment
36	Vessel arrival rate	Flow	vessel/ (mo*berths)	(Expectation_of _vessel_arrival-Number_of_unloaded_vessels)/Time_adjustment+Vessel_departure _rate
37	Berthing_time	Auxiliary	da/vessel	(Time_period_of_crane_operation/Berths_equivalent)*(Tonnage_of_vessel/(number _of_cranes*Crane_productivity))
38	Productivity of crane	Auxiliary	tons/ (da*crane)	capacity_of_crane*operation_cycle_of_crane

39	Desired number of cranes	Auxiliary	crane/ berths	MAX(0<<crane/berths>>CEIL(Total_desired_of_ throughput/Crane_productivity,1<<crane/berths>>))
40	Desired number of trucks	Auxiliary	truck/berths	MAX(0<<truck/berths>>CEIL((Desired_throughput_in_WH/Productivity_ of_truck),1<<truck/berths>>))
41	The decreasing of truck rate	Flow	truck/ (mo*berths)	Number_of_trucksAdjustment_time _for_decreasing _truck
42	The increasing of truck rate	Flow	truck/ (mo*berths)	(Desired_number_of_trucks-Number_of_trucks)/Adjusment_time_for_increasing_of_ truck+The_decreasing_of_ truck_ rate
43	Expectation of vessel arrival	Auxiliary	vessel/ berths	Total_desired_of_ throughput/Tonnage_of_vessel
44	Incoming rate of cargo in WH	Flow	tons/mo	Number_of_trucks*Number_of_berths*'Productivity_ of_truck'
45	Change in order expectation (WH)	Flow	tons/mo^2	(Order_rate_in_ WH-Expectation_of_ order_WH)/Adjustment_time_of_expectation_WH
46	Delivery rate of cargo in WH	Flow	tons/mo	Order_rate_in_ WH
47	Expectation of desired throughput in WH	Auxiliary	tons	Expectation_of_ order_WH*Coverage_time_ for_safety_stock_ in _WH
48	Desired throughput in WH	Auxiliary	tons/ (mo*berths)	((Expectation_of_ order_WH+(Expectation_of_ desired_throughput_in_WH-Safety_stock_in warehouse_WH)/Adjustment_time_ for_changing_ throughput_in_WH)/Number_of_berths)

D.1.3: Decision and respond variables of the port operation

No	Decision Variables (Input)	Respond Variables (Output)
1	Customer order rate in warehouse	Berth occupancy ratio (BOR)
2	Customer order rate in stockpile yard	Vessel waiting time
3	Load of vessel	Cargo throughput
4	Capacity of truck	Number of unloaded vessels
5	Cycle number of truck operation	Number of trucks
6	Cycle number of tugboat operation	Number of cranes
7	Capacity of tugboat	Number of tugboats
8	Length of conveyor	Speed of conveyor
9	Capacity of conveyor	
10	Operation cycle of crane	
11	Lifting capacity of crane	

D.2: Constants, functions, and equations in the port quality level

D.2.1: Constants in the port quality level

No	Constants	Unit	Values
1	Budget for inspector per month	USD	7446.33<<USD>>
2	Actual number of Inspectors per Vessel	person/vessel	10<<person/vessel>>
3	Number of training workers	person	3<<person>>
4	Compensation cost for unavailability	USD/hr	228<<USD/hr>>
5	Compensate cost per unavailable worker	USD/person	40<<USD/person>>
6	Actual % of undetected damaged from Internal Failure	%	0<<%>>
7	Cost per complaint	USD/complaint	3077<<USD/complaint>>
8	Cost per lost cargo	USD/Tons	254<<USD/Tons>>
9	Actual lost cargo Rate	%	0.12<<%>>
10	Actual damaged Rate	%	0.03<<%>>
11	Adjustment time	mo	1<<mo>>

12	Cost per Damaged Cargo	USD/Tons	190.5<<USD/Tons>>
13	Repair Time per Transporter Item	hr/item	4.91<<hr/item>>
14	Demurrage Cost per hour	USD/hr	291.67<<USD/hr>>
15	Repair Time per Equipment item	hr/item	7.8<<hr/item>>
16	Repair cost per equipment item	USD/item	3610<<USD/item>>
17	AC Decision making adjustment for safety & security		25<<%>>*Discrepancy for decision_making
18	Repair cost per transporter item	USD/item	653<<USD/item>>
19	Safety & security Budget per month	USD	38877.5<<USD>>
20	Actual safety & security cost per month	USD/mo	577<<USD/mo>>
21	Checking cost per Transporter	USD/Item	3<<USD/Item>>
22	Checking cost per Equipment	USD/item	817<<USD/item>>
23	Transporter budget per month	USD	256.42<<USD>>
24	Equipment budget per month	USD	72948.72<<USD>>
25	PC decision making adjustment for maintenance		50<<%>>* Discrepancy for decision making
26	Maintenance time per equipment item	hr/item	0.6<<hr/item>>
27	Maintenance time per transporter item	hr/item	2<<hr/item>>
28	Preventive maintenance cost for transporter	USD/item	20.7<<USD/item>>
29	Actual number of transporter maintenance items	<<item>>	277<<item>>
30	Preventive maintenance cost for equipment	USD/item	1277<<USD/item>>
31	Actual number of equipment maintenance items	<<item>>	17<<item>>
32	AC decision making adjustment for inspector		25<<%>>*Discrepancy for decision making
33	Cost per inspector	USD/person	5.83<<USD/person>>
34	Checking cost per transporter item	USD/item	3<<USD/item>>
35	Checking cost per equipment item	USD/item	817<<USD/item>>
36	Target COQ rate	%	20<<%>>
37	ISO 9000 audit cost	USD	2461.54<<USD>>
38	Target non-conformance cost	USD	76.2<<USD>>
39	Draft survey cost per cargo	USD/Tons	0.0125<<USD/Tons>>
40	Customer clearance cost per cargo	USD/Tons	0.1458<<USD/Tons>>

41	Quality improvement research cost	USD	1000<<USD>>
42	SOP making cost	USD	0<<USD>>
43	Other complement costs of recruitment	USD	2352.67<<USD>>
44	Cost per training	USD/training	584.9<<USD/training>>
45	Number of trainings	training/person	8<<training/person>>
46	Number of workers on training	person	3<<person>>
47	Cost per month	USD/month	6923.077<<USD/mo>>
48	Cost per doctor	USD/doctor	61.54<<USD/doctor>>
49	Number of doctors	doctor	30<<doctor>>
50	Cost_ per psycho test consultant	USD/consultant	13.85<<USD/consultant>>
51	Number of psycho test consultants	consultant	120<<consultant>>
52	Questionnaire making cost	USD	3.56<<USD>>

D.2.2: Functions and equations in the port quality level

No.	Variables	Type	Unit	Equations
1	Amount of damaged cargo after shipping	Stock	Tons	Amount_of_Damaged_after_Shipping= INTEGRAL (Rate of damaged after shipping -Discard out rate of damaged after shipping) + 0<<Tons>>
2	Lost cargo cost	Stock	USD	Lost_Cargo_Cost= INTEGRAL (Lost cargo cost rate - discard out rate of lost cargo) + 0<<USD>>
3	Cargo damaged cost	Stock	USD	Cargo_Damaged_Cost = INTEGRAL (Cargo damaged cost rate -discard out rate of cargo damaged cost) + 0<<USD>>
4	Number of inspectors	Stock	person/ vessel	Number_of_inspectors = INTEGRAL (Inspector adding rate-inspector discard out rate) + Actual_Number_of_Inspectors_per_Vessel
5	Opportunity cost	Stock	USD	Opportunity cost = INTEGRAL (Opportunity cost rate-Discard out rate of opportunity cost) + 0<<USD>>
6	Transporter to be checked	Stock	Transporter	Transporter_to_be_ checked = INTEGRAL (Checked transporter rate-Discard out rate of checked transporter) + 0<<Transporter>>
7	Equipment to be checked	Stock	equipment	Equipment_to_be_ checked = INTEGRAL (Checked equipment rate-Discard out rate of checked equipment) + 0<<equipment>>
8	External failure cost	Stock	USD	External_Failure_Cost = INTEGRAL (External failure cost rate- discard out rate of external failure cost) + 0<<USD>>
9	Amount of damaged cargo	Stock	Tons	Amount of damaged cargo= INTEGRAL (Damaged cargo rate-Discard out rate of damaged cargo) + 0<<Tons>>
10	Amount of lost cargo	Stock	Tons	Amount of lost cargo = INTEGRAL (Amount of lost cargo rate-Discard out rate of lost cargo) + 0<<Tons>>
11	Delay due to maintenance	Stock	hour	Delay due to maintenance = INTEGRAL (Delay rate due to maintenance - Discard out delay rate due to maintenance) + 0<<hr>>
12	Delay due to repair	Stock	hour	Delay due to repair = INTEGRAL (Delay due to repair rate-Discard out delay rate due to repair rate) + 0<<hr>>
13	Demurrage Cost	Stock	USD	Demurrage cost = INTEGRAL (Demurrage cost rate-Discard out rate of demurrage cost) + 0<<USD>>
14	Equipment to be repaired	Stock	equipment	Equipment to be repaired = INTEGRAL (Transporter to be repaired rate- Discard out rate of transporter to be repaired) + 0<<equipment>>
15	Transporter to be repaired	Stock	Transporter	Transporter to be repaired = INTEGRAL (Equipment to be repaired rate- Discard out rate of equipment to be repaired) + 0<<Transporter>>
16	Budget to spend for safety and security cost	Stock	USD/month	Budget to spend for safety and security cost= INTEGRAL (budget rate-Discard out rate of budget rate) + Actual_safety_and_security cost_per _month
17	Equipment maintenance cost	Stock	USD	Equipment maintenance cost = INTEGRAL (Equipment maintenance cost rate- Discard out rate of equipment maintenance cost) + 0<<USD>>

18	Number of equipment maintenance items	Stock	item	Number of equipments = INTEGRAL (number of equipments rate-Discard out rate of number of equipments) + Actual_Number_of_Equipment_maintenance items
19	Transporter maintenance cost	Stock	USD	Transporter maintenance cost = INTEGRAL (Transporter maintenance cost rate-Discard out rate of Transporter maintenance cost) + 0<<USD>>
20	Number of transporter maintenance items	Stock	item	Number of transporters = INTEGRAL (Number of transporters rate-Discard out rate of number of transporters) + Actual_Number_of_Transporter_maintenance items
21	Internal failure cost	Stock	USD	Internal failure cost = INTEGRAL (Internal failure cost rate-Discard out rate of Internal failure cost) + 0<<USD>>
22	Appraisal cost	Stock	USD	Appraisal Cost = INTEGRAL (Appraisal cost rate-Discard out rate of appraisal cost) + 0<<USD>>
23	Prevention cost	Stock	USD	Prevention cost = INTEGRAL (Prevention cost rate-Discard out rate of prevention cost) + 0<<USD>>
24	Repair cost	Stock	USD	Repair cost = INTEGRAL (Repair cost rate-Discard out rate of repair cost) + 0<<USD>>
25	Conformance Cost	Stock	USD	Conformance cost = INTEGRAL (Conformance cost rate-Discard out rate of Conformance cost) + 0<<USD>>
26	Non-conformance cost	Stock	USD	Non-conformance cost = INTEGRAL (Non-conformance cost rate-Discard out rate of Non-conformance cost) + 0<<USD>>
27	Cost of poor quality (COPQ)	Stock	USD	Cost of Poor Quality = INTEGRAL (Rate of COPQ change-Discard out rate of COPQ change) + 0<<USD>>
28	Prevention cost (PC) and appraisal cost (AC) effect lost adjustment	Auxiliary	%	(0.7*%_Safety_&_Security_Cost_to_Prevention_Cost)+(0.3*%_of_Cargo_Inspe ction_to_Appraisal_Cost)
29	Number of transporter maintenance items adjustment	Auxiliary	item	ROUND('Number_of_transporter_maintenance_items_added+Actual_num_of_ transporter_items_ adj)
30	Number of equipment maintenance items added adjustment	Auxiliary	item	ROUND(Actual_num_of_ Eqp_maintenance_items_adj+Num_of_eqp_ maintenance_items_added)
31	Compensation cost from unavailability due to maintenance	Auxiliary	USD	Delay_due_to_maintenance*compensation_cost_for_unavailability
32	Checked transporter of prevention cost (PC) effect adjustment	Auxiliary	item	MAX(ROUND(GRAPH(PC_effect_maintenance_transporter,0<<%>>,1.4<<%>>,{395,194,113,72,48,32,22,15,10,7,5,3,2,1,1}<<item>>)),0<<item>>)
33	Checked equipment of prevention cost (PC) effect adjustment	Auxiliary	item	MAX(ROUND(GRAPHCURVE('PC_effect_maintenance_equipment',0<<%>>,5 <<%>>,{36,27,20,15,11,9,7,5,5,4,4,5,6,7}<<item>>)),0<<item>>)
34	Actual number of complaints	Auxiliary	complaint	ROUND(NORMAL(4<<complaint>>,0.5<<complaint>>))

35	Equipment repaired of prevention cost (PC) effect adjustment	Auxiliary	item	MAX(ROUND(GRAPHCURVE(PC_effect_maintenance_equipment,0<<%>>,5<<%>>,{36,27,20,15,11,9,7,5,5,4,4,5,6,7}<<item>>)),0<<item>>)
36	Repaired transporter of prevention cost (PC) effect adjustment	Auxiliary	item	MAX(ROUND(GRAPH(PC_effect_maintenance_transporter,0<<%>>,1.4<<%>>,{395,194,113,72,48,32,22,15,10,7,5,3,2,1,1,0,0,0}<<item>>)),0<<item>>)
37	% of equipment maintenance	Auxiliary	%	MAX(NORMAL(8.42<<%>>,9.45<<%>>),0<<%>>)
38	Actual number of equipment maintenance items adjustment	Auxiliary	item	Actual_Num_of_Equipment_maintenance_items*%_of_equipment _maintenance
39	Equipment discard out rate	Flow	item/month	Num_of_eqp_maintenance_items/Adj_Time
40	Equipment adding rate	Flow	item/month	Num_of_eqp_maintenance_items_added_adj/Adj_Time
41	Preventive maintenance for equipment cost	Auxiliary	USD	Number_of_Equipments*Prev_Maintenance_cost_ for_eqp_per_item
42	Actual number of transporter items adjustment	Auxiliary	item	%_of_transporter_maintenance*Actual_Number_of_transporter_maintenance_ items
43	% of transporter maintenance	Auxiliary	%	MAX(NORMAL(8.33<<%>>,3.35<<%>>),0<<%>>)
44	Transporter discard out rate	Flow	item/month	(number_of_transp_maintenance_item-Actual_num_of_transporter_item_adj)/Adj_Time
45	Transporter adding rate	Flow	item/month	Number_of_Transporter_ maintenance_items_adj/Adj_Time
46	Number of transporters	Auxiliary	item	Number_of_transp_ maintenance_items
47	Transporter maintenance time	Auxiliary	hour	Number_of_Transporters*'Maintenance_Time_per_Transporter_ item'
48	Preventive maintenance cost for transporter	Auxiliary	USD	Prev_Maintenance_cost_ for_transporter_per_item*'Number_ of_Transporters
49	Inspector discard out rate	Flow	person/ (month* vessel)	(number_of_inspectors-Actual_Number_of_Inspectors_per_Vessel)/Adj_Time
50	Inspector adding rate	Flow	person/ (month* vessel)	Number_of_Inspectors_added/Adj_Time
51	Discard out rate cost of poor quality (COPQ) change	Flow	USD/month	Cost_of_Poor_Quality_COPQ/Adj_Time
52	Total cost of poor quality (COPQ)	Auxiliary	USD	Opportunity_Cost+Conformance_Cost+Non_Conformance_Cost
53	Discard out rate of opportunity cost	Flow	USD/month	Opportunity_Cost/Adj_Time
54	Opportunity cost rate	Flow	USD/month	Total_Opportunity_Cost/Adj_Time
55	Compensation cost for Worker on training	Auxiliary	USD	Compensation_Cost_per_unavailable _worker*Num_of_Workers_on_training

56	Compensation cost for transporter and equipment	Auxiliary	USD	Compensation_Cost_from_unavailability_due_to_maintenance+Compensation Cost_from_unavailability_due_to_repair
57	Compensation cost from unavailability due to repair	Auxiliary	USD	Delay_due_to_repair*compensation_cost_for_unavailability
58	Compensation cost from lost and damaged cargo	Auxiliary	USD	(IF(number_of_damaged_cargo>0<<Tons>>,number_of_damaged_cargo*190.5<<USD/Tons>>,0<<USD>>))+(IF(num_of_loss_cargo>0<<Tons>>,num_of_loss_cargo*254<<USD/Tons>>,0<<USD>>))
59	Total opportunity cost	Auxiliary	USD	Compensation_Cost_for_Worker_on_Training+Compensation_Cost_for_transporter_and_equipment+Compensation_Cost_from_lost_and_damaged_cargo
60	Discard out rate of checked transporter	Flow	item/month	Transporter_to_be_checked/Adj_Time
61	Checked transporter check	Flow	item/month	Checked_transporter_of_PC_effect_adj/Adj_Time
62	Checked equipment rate	Flow	item/month	Checked_equipment_of_PC_ effect_adj/Adj_Time
63	Discard out rate of checked equipment	Flow	item/month	Equipment_to_be_checked/Adj_Time
64	Discard out rate appraisal cost	Flow	USD/month	Appraisal_cost/Adj_Time
65	Discard out rate of conformance-cost	Flow	USD/month	Conformance_Cost/Adj_Time
66	Total prevention and appraisal cost	Auxiliary	USD	Appraisal_cost+Prevention_cost
67	Discard out rate of non-conformance cost	Flow	USD/month	Non_Conformance_Cost/Adj_Time
68	Total failure cost	Auxiliary	USD	External_Failure_Cost+Internal_failure_cost
69	Discard out rate of Internal failure cost	Flow	USD/month	Internal_failure_cost/Adj_Time
70	Discard out rate of external failure cost	Flow	USD/month	External_Failure_Cost/Adj_Time
71	Discard rate of damaged cargo after shipping	Flow	Tons/month	Amount_of_Damaged_after_Shipping/Adj Time
72	External failure cost rate	Flow	USD/month	Total_External_Failure_Cost/Adj_Time
73	Discount due to damaged cost	Auxiliary	USD	Cost_per_Cargo_ Damaged*Amount_of_Damaged_after_Shipping
74	Undetected damaged cargo from internal failure (IF)	Auxiliary	Tons	%_of_undetected damaged_from_IF*Damaged_cargo_adj
75	Rate of damaged cargo after shipping	Flow	Tons/month	Undetected_ Damaged_from_IF/Adj Time

76	% of undetected damaged cargo from internal failure (IF)	Auxiliary	%	IF(Actual_%_of_undetected_damaged_from_Internal_Failure=0<<%>>,0<<%>>,Actual_%_of_undetected_damaged_from_Internal_Failure-AC_and_PC_ effect_damaged*'Actual_%_of_undetected_damaged_from_Internal_Failure'))
77	Total external failure cost	Auxiliary	USD	Complaint_ Adjustment_Cost+Discount_due_ to_Damaged_Cost
78	Lost cargo cost adjustment	Auxiliary	USD	Amount_of_lost_cargo*Cost_per_Loss_Cargo
79	Damaged cargo cost adjustment	Auxiliary	USD	Amount_of_damaged_cargo*'Cost_per_Cargo_ Damaged'
80	Discard out rate of damaged cargo	Flow	Tons/month	Amount_of_damaged_cargo/Adj_Time
81	Damaged cargo rate	Flow	Tons/month	Damaged_cargo_adj/Adj_Time
82	Discard out rate of damaged cargo cost	Flow	USD/month	Damaged_Cargo_Cost/Adj_Time
83	Discard out rate of lost cargo cost	Flow	USD/month	Lost_Cargo_Cost/Adj_Time
84	Discard out rate of lost cargo	Flow	Tons/month	Amount_of_lost_cargo/Adj_Time
85	Lost cargo rate	Flow	Tons/month	Lost_cargo/Adj_Time
86	Appraisal cost (AC) and prevention cost (PC) effect damaged cargo	Auxiliary	%	DELAYINF(AC_and_PC_effect_damaged_adj,Delay_Time_for_Decision_ Making,3,AC_and_PC_effect_ damaged_adj)
87	Prevention cost (PC) and appraisal cost (AC) effect lost cargo	Auxiliary	%	DELAYINF(PC_and_AC_effect_lost_adj,Delay_Time_for_Decision_Making,3, PC_and_AC_effect_ lost_ adj)
88	Lost Cargo Cost Rate	Flow	USD/monht	Lost_cargo_cost_adj/Adj_Time
89	% Safety and security cost to prevention cost	Auxiliary	%	Safety_and_ Security_Cost/Prevention_Cost_ adj*100<<%>>
90	% of cargo inspection to appraisal cost	Auxiliary	%	Cargo_inspection _Cost/Appraisal_cost_ adj
91	Lost cargo rate adjustment	Auxiliary	%	MAX(GRAPH(PC_and_AC_effect_loss,0<<%>>,2.1<<%>>,{0.1,0.082,0.068,0.055,0.046,0.037,0.030,0.025,0.02,0.02,0.01,0.007,0.003}<<%>>),0<<%>>)
92	Lost cargo	Auxiliary	Tons	Lost_Cargo_Rate_adj'*Load_of_vessel*Number_of_unloaded_vessels*Number _of_berths*time_period
93	Damaged cargo rate	Auxiliary	%	MAX(GRAPHCURVE('AC_&_PC_effect_damaged',0<<%>>,1.25<<%>>,{0.032 ,0.016,0.0095,0.0066,0.005,0.004,0.003,0.003,0.002,0.0017,0.0014,0.0012,0.0009,0.0008,0.0006,0.0005,0.0004,0.0003,0.0003}<<%>>),0<<%>>)
94	Damaged cargo adjustment	Auxiliary	Tons	ROUND(Damaged_Cargo_Rate*Load_of_vessel*Number_of_unloaded_ vessels *Number_of_berths*time_period,1<<Tons>>)
95	Adjustment time	Auxiliary	month	1<<mo>>
96	Damaged cargo cost rate	Flow	USD/month	Damaged_cargo_cost_adj/Adj_Time

97	Total inspector	Auxiliary	person/ vessel	Number_of_inspectors
98	Cargo inspection cost	Auxiliary	USD	Number of load Vessels*Cost per Inspector*total_inspector
99	Total appraisal cost	Auxiliary	USD	Quality_Audit_Cost+Draft_Survey_Cost+Custom_Clearance_Cost+Cargo_Inspection_Cost+Equipment_Checking_Cost+Transporter_Checking_Cost
100	Number of equipments	Auxiliary	item	Num_of_eqp_maintenance_items
101	Number of transporters	Auxiliary	item	Num_of_transporters
102	Transporter maintenance time	Auxiliary	hour	Number of Transporters*Maintenance Time per Transporter
103	Equipment maintenance time	Auxiliary	hour	Maintenance Time per Equipment item*Number_of_ Equipments
104	Delay rate due to maintenance	Flow	month^-1	Delay_Time_due_to_maintenance/Adj_Time
105	Discard out delay rate due to maintenance	Flow		Delay_due_to_ maintenance/Adj_Time
106	Delay rate due to repair	Auxiliary		Delay_Time_due_to _Repair'/Adj_Time
107	Discard out delay rate due to repair	Auxiliary		Delay_due_to_repair/Adj_Time
108	Discard out rate of demurrage cost	Flow	USD/month	Demurrage_Cost/Adj_Time
109	Demurrage cost adjustment	Auxiliary	USD	Total_delay_time*'Demurrage_Cost _per_hour'
110	Total delay time	Auxiliary	da	delay_due_to_repair+delay_due_to_ maintenance
111	Demurrage cost rate	Flow	USD/month	Demurrage_Cost_ adj/Adj_Time
112	Delay time due to maintenance	Auxiliary	hour	Equipment Maintenance Time+Transporter_ Maintenance_Time
113	Discard out rate of repair cost	Flow	USD/month	Repair_Cost/Adj_Time
114	Equipment to be repaired rate	Flow	item/month	Equipment_ Repaired_of_PC_ effect_adj/Adj_Time
115	Discard out rate of equipment to be repaired	Flow	item/month	Equipment _to_be_repaired/Adj_Time
116	% of preventive maintenance (PM) cost of equipment to total prevention cost	Auxiliary		Equipment_ maintenance_cost/Prevention_Cost_ adj
117	Total repair time for equipment	Auxiliary	hour	iurRepair_Time _per _equipment_item*equipment _to_be_repaired
118	Repair cost of equipment	Auxiliary	USD	Repair_cost_per_ equipment_item*equipment _to_be_repaired
119	Safety and security cost	Auxiliary	USD	Cost per month*Num of months

120	Total prevention cost	Auxiliary	USD	Quality Engineering+Worker_Training_Cost+Safety_and_Security_Cost' +Marketing_Research_Cost+Recruiting_Cost+Preventive_Maintenance_Cost
121	% of preventive maintenance (PM) cost of transporter to Total prevention cost	Auxiliary		Transporter_ maintenance_cost/Prevention_Cost_adj
122	Discard out rate of transporter to be repaired	Flow	item/month	Transporter_to_be_repaired/Adj_Time
123	Transporter to be repaired rate	Flow	item/month	Repaired_ Transporter_of_PC_effect_adj/Adj_Time
124	Discrepancy for decision making	Auxiliary		IF(Target CPOQ Rate>Adj COPQ to Sales,0<<%>>,(Adj COPQ to Sales-Target COPQ Rate))
125	Prevention cost (PC) decision making of adjustment budget	Auxiliary	USD	DELAYINF(PC_adjustment*Safety_and_Security_Budget_per_month,Delay_ Time_for_Decision_Making,1,PC_adjustment*Safety_&_Security Budget_per_month)
126	Cost added for safety and security	Auxiliary	USD	(ROUND(IF(Safety_and_Security Budget_per_month>PC_Decision_ making_of_adjustment_Budget,PC_Decision_ making_of_ adjustment_Budget,0<<USD>>)))
127	Discard out budget rate	Flow	USD/month	(Budget_to_spend_for_safety_and_security cost-Actual_safety_and_ security_cost_per _month)/Adj_Time
128	Budget rate	Flow	USD/month	Cost_added_for_safety_and_security/Adj_Time
129	Discard out rate of prevention cost	Flow	USD/month	Prevention_cost/Adj_Time
130	Equipment maintenance cost discard out rate	Flow	USD/month	Equipment_ maintenance_cost'/Adj_Time
131	Equipment maintenance cost rate	Flow	USD/month	Prev_Maintenance_ for_Equipment_Cost/Adj_Time
132	Prevention cost (PC) effect maintenance equipment	Flow		DELAYINF(%_of_PM_Cost_to_Total_Prevention_Cost,Delay_Time_for_ Decision_Making,1,%_of_PM_Cost_to_Total_Prevention_ Cost)
133	Transporter cost discard out rate	Flow	USD/month	Transporter_maintenance_cost/Adj_Time
134	Transporter maintenance cost rate	Flow	USD/month	Preventive_maintenance_cost_for_transporter/Adj_Time
135	Prevention cost (PC) effect maintenance transporter	Flow		DELAYINF(%_of_PM_Cost_for_Transporter_to_Total_Prevention_Cost,Delay_ Time_for_Decision_Making',1,'%_of_PM_Cost_for_Transporter_to_Total_ Prevention_Cost')
136	Internal failure cost rate	Flow	USD/month	Internal_failure_cost_adj/Adj_Time
137	Appraisal cost rate	Flow	USD/month	Appraisal_cost_adj/Adj_Time
138	Prevention cost rate	Flow	USD/month	Prevention_Cost_ adj/Adj_Time

139	Transporter checking cost	Auxiliary	USD	Checking_Cost_per _Transporter_item*transporter_to_be_checked
140	Equipment checking cost	Auxiliary	USD	Checking_Cost_per_Equipment_ item*equipment_to_be_checked
141	Discrepancy for decision making	Auxiliary	%	IF(Target_COPQ_Rate>Desired_COPQ_Rate,0<<%>>,(Desired_COPQ_Rate-Target_COPQ_Rate))
142	Number of transporter maintenance items added	Auxiliary	item	ROUND(IF(Transporter_Budget_per_month>PC_Decision_making_adjustment_Budget_for_Transporter,PC_Decision_making_adjustment_Budget_for_Transporter'/'Prev_Maintenance_cost_for_transporter_per_item,0<<item>>))
143	Prevention cost (PC) decision making adjustment budget for transporter	Auxiliary	USD	DELAYINF(PC_ Decision_making_adjustment_for_maintenance'*'Transporter_Budget_per_month,Delay_Time_for_Decision_Making,1,PC_Decision_making_adjustment_for_maintenance*Transporter_ Budget_per_month)
144	Number of equipment_ maintenance items added	Auxiliary	item	ROUND(IF(Equipment_Budget_per_month>PC_Decision_making_adjustment_Budget_for_Equipment,PC_Decision_making_adjustment_Budget_for_Equipment/Prev_Maintenance_cost_ for_eqp_per_item',0<<item>>))
145	Prevention cost (PC) decision making adjustment budget for equipment	Auxiliary	USD	DELAYINF(PC_Decision_making_adjustment_for_maintenance*Equipment_Budget_per_month,Delay_Time_for_Decision_Making,1,PC_Decision_making_adjustment_for_maintenance*Equipment_Budget_per_month)
146	Prevention cost (PC) decision making adjustment for maintenance	Auxiliary		50<<%>>*Discrepancy_for_decision_Making
147	Preventive maintenance cost	Auxiliary	USD	Transporter_maintenance_cost+equipment_maintenance_cost
148	Number of inspectors added	Auxiliary	person/ vessel	ROUND(IF(Inspector_Budget _per_vessel>AC_Decision_making_adjustment_Budget,AC_Decision_making_adjustment_Budget/Cost_per_Inspector,0<<person/vessel>>))

D.2.3: Decision and respond variables of the port quality level

No	Decision Variables (Input)	Respond Variables (Output)
1	Cost added for safety & security	Repair cost
2	Number of transporter maintenance items added	Demurrage cost
3	Number of equipment maintenance items added	Lost cargo cost
4	Number of inspectors added	Damaged cost
5	Number of equipment items to be checked	Internal failure cost
6	Number of transporter items to be checked	External failure cost
7	Number of equipment breakdown items added	Conformance cost
8	Number of transporter breakdown items added	Non-conformance cost
9	Amount of lost cargo	Opportunity cost
10	Amount of damaged cargo	Cost of poor quality
11	Amount of damaged cargo after shipping	Prevention cost
		Appraisal cost

D.3: Constants, functions, and equations in the port performance metrics

D.3.1: Constants in the port performance metrics

No	Constants	Unit	Value
1	Number of CTQ		3
2	Time period	mo	1<<mo>>
3	Number of berths	berth	10<<berth>>
4	Available time of transporter	hour	720<<hr>>
5	Available time of equipment	hour	720<<hr>>
6	Value of sigma factor to Cpk	sigma	3<<sigma>>
7	Cpk conversion	Cpk	1<<Cpk>>

D.3.2: Functions and equations in the port performance metrics

No.	Variables	Type	Unit	Equations
1	Sigma value for delay time	Auxiliary	sigma	(IF((NORMINV((1000000-'Defects per Million Opportunities_DPMO_of_Delay_Time')/1000000)+1.5)>6,6,(NORMINV((1000000 -Defects per Million Opportunities_DPMO_of_Delay_Time)/1000000)+1.5))) *Sigma_conversion
2	Sigma value for transporter breakdown	Auxiliary	sigma	(IF((NORMINV((1000000-Defects per Million Opportunities_ DPMO_of_ Transporter_breakdown)/1000000)+1.5)>6,6,(NORMINV((1000000-'Defects per Million_Opportunities_DPMO_of_Transporter_breakdown)/1000000)+1.5)))* Sigma_conversion
3	Sigma value for equipment breakdown	Auxiliary	sigma	(IF((NORMINV((1000000-Defects_per_Million_Opportunities_ DPMO_of_equipment_ breakdown)/1000000)+1.5)>6,6,(NORMINV((1000000-Defects per Million Opportunities_DPMO_of_equipment_ breakdown)/1000000)+1.5)))*Sigma_conversion
4	Process capability indices equipment breakdown	Auxiliary	Cpk	Sigma_value_for_ Equipment_breakdown/Value_of Sigma_factor_ to_Cpk*Cpk_conversion
5	Sigma value for damaged cargo	Auxiliary	sigma	(IF((NORMINV((1000000-DPMO_Damaged_ cargo)/1000000)+1.5)>6,6,(NORMINV((1000000-DPMO_Damaged_ cargo)/1000000)+1.5)))*Sigma_conversion
6	Process capability indices for damaged cargo	Auxiliary	Cpk	Sigma_value_for_ damaged_cargo/Value_of Sigma_factor_ to_Cpk*Cpk_conversion
7	Defects per million opportunities (DPMO) of equipment breakdown	Auxiliary		((Total_Repair_Time _for_Equipment/(Available_time_of_ equipment*Number_of _CTQ_repair_time_of_equipment))*1000000)
8	Defects per million opportunities (DPMO) of transporter breakdown	Auxiliary		(('Total_Repair_Time_ for_Transporter'/('Available_time_of_ transporter'*'Number_of _CTQ_repair_time_of_transporter'))*1000000)
9	Total of service time	Auxiliary	day	Service_time*Number_of_unloaded_vessels*Number_of_berths

10	Process capability indices (Cpk) of delay time	Auxiliary	Cpk	Sigma_value_for_ delay_time/Value_of Sigma_factor_ to_Cpk*Cpk_conversion
11	Defects per million opportunities (DPMO) of delay time	Auxiliary		(Total_delay_time/(Total_of_ service_time*Number_of_CTQ_ delay_time))*1000000
12	Defects per million opportunities (DPMO) damaged cargo	Auxiliary		((amount_of_damaged_cargo/(Load_of_vessel*Number_of_CTQ_Damaged* Number_of_unloaded_vessels*time_period*Number_of_berths))*1000000)
13	Sigma value for lost cargo	Auxiliary	sigma	(IF((NORMINV((1000000-Defects_per_Million_Opportunities_DPMO_ of_Lost_cargo)/1000000)+1.5)>6,6,(NORMINV((1000000-Defectsper_Million_ Opportunities_DPMO_of_Lost_cargo)/1000000)+1.5)))*Sigma_conversion
14	Process capability indices (Cpk) of lost cargo	Auxiliary	Cpk	Sigma_value_for_ lost_cargo/Value_of Sigma_factor_ to_Cpk*Cpk_conversion
15	Defects per Million opportunities (DPMO) of lost_cargo	Auxiliary		((amount_of_lost_cargo/(Load_of_vessel*Number_of_CTQ*Number_of_unloaded _vessels*time_period*Number_of_berths))*1000000)

D.3.3: Decision and respond variables of the port performance metrics

No	Decision Variables (Input)	Respond Variables (Output)
1	Total delay time	Sigma Value and Process Capability Indices (Cpk) for delay time
2	Amount of lost cargo	Sigma Value and Process Capability Indices (Cpk) for lost cargo
3	Amount of damaged cargo	Sigma Value and Process Capability Indices (Cpk) for damaged cargo
4	Total repair time for equipment	Sigma Value and Process Capability Indices (Cpk) for equipment breakdown
5	Total repair time for transporter	Sigma Value and Process Capability Indices (Cpk) for transporter breakdown
6	Available time of equipment	
7	Available time of transporter	
8	Total of service time	
9	Load of vessel	

Appendix E: Data of the relationship between variables

E.1: Data of the relationship between the berth occupancy ratio (BOR) and the delay factor (Monie, 1987)

Berth	Number of Berths														
Occupancy	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.050	0.053	0.003	0	0	0	0	0	0	0	0	0	0	0	0	0
0.100	0.111	0.010	0.001	0	0	0	0	0	0	0	0	0	0	0	0
0.150	0.176	0.023	0.004	0.001	0	0	0	0	0	0	0	0	0	0	0
0.200	0.250	0.042	0.010	0.003	0.001	0	0	0	0	0	0	0	0	0	0
0.250	0.333	0.067	0.020	0.007	0.003	0.001	0	0	0	0	0	0	0	0	0
0.300	0.429	0.099	0.033	0.013	0.006	0.003	0.001	0.001	0	0	0	0	0	0	0
0.350	0.538	0.140	0.053	0.023	0.011	0.006	0.003	0.002	0.001	0.001	0	0	0	0	0
0.400	0.667	0.190	0.078	0.038	0.020	0.011	0.006	0.004	0.002	0.001	0.001	0.001	0	0	0
0.450	0.818	0.254	0.113	0.058	0.033	0.020	0.012	0.008	0.005	0.003	0.002	0.002	0.001	0.001	0.001
0.500	1.000	0.333	0.158	0.087	0.052	0.033	0.022	0.015	0.010	0.007	0.005	0.004	0.003	0.002	0.002
0.550	1.222	0.434	0.217	0.126	0.079	0.053	0.037	0.026	0.019	0.014	0.010	0.008	0.006	0.005	0.004
0.575	1.353	0.494	0.254	0.151	0.097	0.066	0.047	0.034	0.025	0.019	0.014	0.011	0.009	0.007	0.005
0.600	1.500	0.562	0.296	0.179	0.118	0.082	0.059	0.044	0.033	0.025	0.020	0.016	0.012	0.010	0.008
0.625	1.667	0.641	0.344	0.213	0.143	0.101	0.074	0.056	0.043	0.034	0.027	0.021	0.017	0.014	0.012
0.65	1.857	0.732	0.401	0.253	0.173	0.124	0.093	0.071	0.055	0.044	0.035	0.029	0.024	0.02	0.016
0.675	2.077	0.837	0.468	0.301	0.209	0.152	0.115	0.09	0.071	0.057	0.047	0.038	0.032	0.027	0.023
0.700	2.333	0.961	0.547	0.357	0.252	0.187	0.143	0.113	0.091	0.074	0.061	0.051	0.043	0.037	0.031
0.725	2.636	1.108	0.642	0.426	0.305	0.299	0.178	0.142	0.115	0.095	0.080	0.067	0.058	0.049	0.043
0.750	3.000	1.286	0.757	0.509	0.369	0.281	0.221	0.178	0.147	0.123	0.104	0.089	0.076	0.066	0.058
0.775	3.444	1.504	0.899	0.614	0.451	0.347	0.276	0.225	0.187	0.158	0.135	0.117	0.102	0.089	0.079
0.800	4.000	1.778	1.079	0.746	0.554	0.431	0.347	0.286	0.240	0.205	0.176	0.154	0.135	0.119	0.106
0.825	4.214	2.131	1.311	0.917	0.689	0.543	0.441	0.367	0.311	0.267	0.232	0.204	0.181	0.161	0.145
0.850	5.667	2.604	1.623	1.149	0.873	0.693	0.569	0.477	0.408	0.353	0.310	0.274	0.245	0.220	0.199
0.875	7.000	3.267	2.062	1.476	1.132	0.908	0.751	0.635	0.547	0.478	0.422	0.376	0.338	0.306	0.278
0.900	9.000	4.263	2.724	1.969	1.525	1.234	1.028	0.877	0.761	0.669	0.594	0.533	0.482	0.439	0.402
0.925	12.333	5.926	3.829	2.796	2.185	1.782	1.497	1.285	1.122	0.993	0.888	0.802	0.729	0.668	0.614
0.950	19.000	9.256	6.047	4.457	3.511	2.885	2.441	2.110	1.855	1.651	1.486	1.348	1.233	1.134	1.049
0.975	38.999	19.252	12.708	9.451	7.504	6.211	5.291	4.602	4.068	3.642	3.295	3.006	2.762	2.553	2.373

E.2: Data of the relationship between variables by the expert judgement

The prevention cost effect (%)	The transporter breakdowns (items)	The prevention cost effect (%)	The equipment breakdowns (items)	The prevention plus appraisal cost effect (%)	The lost cargo rate (%)	The prevention plus appraisal cost effect (%)	The damaged cargo rate (%)
0.0	395	0	36	0.0	0.100	0.00	0.0320
1.4	194	5	27	2.1	0.082	1.25	0.0160
2.8	113	10	20	4.2	0.068	2.50	0.0095
4.2	72	15	15	6.3	0.056	3.75	0.0066
5.6	48	20	11	8.4	0.046	5.00	0.0050
7.0	32	25	9	10.5	0.037	6.25	0.0039
8.4	22	30	7	12.6	0.030	7.50	0.0032
9.8	15	35	5	14.7	0.025	8.75	0.0026
11.2	10	40	5	16.8	0.020	10.00	0.0021
12.6	7	45	4	18.9	0.015	11.25	0.0017
14.0	5	50	4	21.0	0.011	12.50	0.0014
15.4	3	55	5	23.1	0.007	13.75	0.0012
16.8	2	60	6	25.2	0.003	15.00	0.0009
18.2	1	65	7			16.25	0.0008
19.6	1					17.50	0.0006
21.0	1					18.75	0.0005
22.4	0					20.00	0.0004
23.8	0					21.25	0.0003
25.2	0					22.50	0.0003